USL C++ Language System

Release 3.0

Product Reference Manual
Release Notes
Library Manual
Selected Readings

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Product Reference Manual

The *C++ Language System Release 3.0 Product Reference Manual* is not included here. You can find the complete *Product Reference Manual* along with other information about C++ in *The C++ Programming Language* by Bjarne Stroustrup, which you received with your HP C++ documentation.

Ordering Additional Copies of These Manuals

You can order additional copies of the following manuals by contacting USL (UNIX System Laboratories, Inc.) and providing the title of the manual you want:

- *C++ Language System Release 3.0 Product Reference Manual*
- *C++ Language System Release 3.0.1 Selected Readings*
- *C++ Language System Release 3.0 Library Manual*
- *C++ Language System Release 3.0.1 Release Notes*

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C++ Language System Release 3.0.1

Release Notes

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Preface

Preface

The C++ *Language System Release Notes* describe Release 3.0.1 of the C++ Language System. This release corrects some problems which were found with the implementation of templates in Release 3.0. The only changes to this manual relate to those fixes. These include the removal of some known problems from Appendix A, the addition of some "Not Implemented" messages to Appendix C, and a note in the CC manual page indicating that the `-ptt` option is obsolete. Chapters 7 and 8 of the *Selected Readings* have also been updated to reflect changes in the template implementation.

This manual is part of a set of four documents that are supplied with your C++ Language System. The other documents are:

- the *Product Reference Manual,* which provides a complete definition of the C++ language supported by Release 3.0 of the C++ Language System
- the *Selected Readings,* which contains papers describing aspects of the C++ language
- the *Library Manual,* which describes the three C++ class libraries and tells you how to use them.

The *Release Notes* consist of four chapters and two appendices, which describe how to install and use the translator, changes in the C++ language for this release, and other information you need to know:

- Chapter 1 is a general description of the C++ Language System and new features that are part of this release. You should read this chapter as a general introduction to the release.
- Chapter 2 is a description of the contents of Release 3.0. This chapter includes a diagram of the contents of the tape from which you install the C++ Language System. You can use this diagram and the accompanying descriptions as a reference when you install and use the C++ Language System.
- Chapter 3 tells you how to install the C++ Language System and how to port it to machines for which it is not directly supported.
- Chapter 4 covers compatibility between different releases of the C++ Language System; it describes things that have changed and might require you to make changes in code written for previous releases. This chapter discusses the following release changes:
  - upgrading from Release 2.0 or Release 2.1 to Release 3.0
  - future compatibility — changes and enhancements that are planned for the next major release of the C++ Language System

  This chapter contains detailed discussions of new features and changes included in the release, and, as such, should be an important reference for all users.
- Appendix A describes known problems with the C++ Language System which are of general interest to C++ programmers, and suggests workarounds for these problems.
- Appendix B describes implementation specific behavior.
- Appendix C is a list of "not implemented" messages issued by Release 3.0.1

- Appendix D contains manual pages for the C++ Language System.

To make the best use of the *Release Notes,* you must be familiar with the C programming language and the C programming environment under the UNIX operating system.

1 Introduction

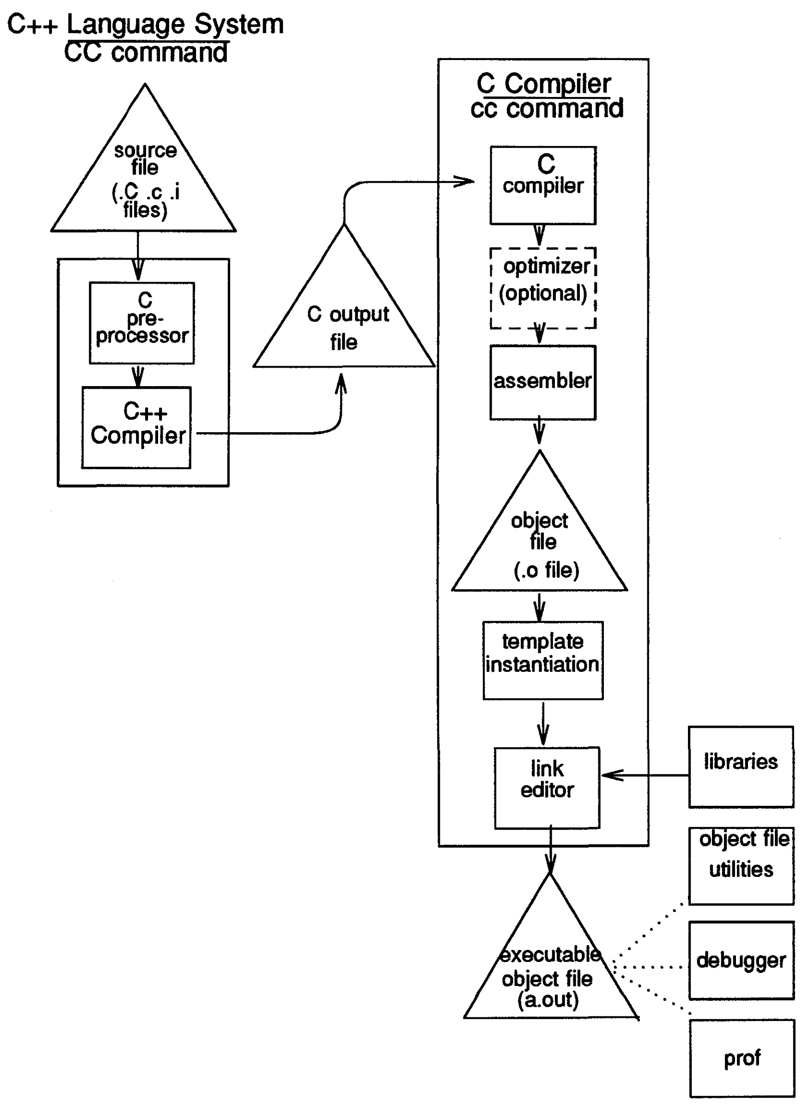
Introduction

The C++ Language System

The C++ Language System, Release 3.0, translates C++ source code to C source code. It supports the C++ programming language (as described in the *C++ Language System Product Reference Manual*). The CC command invokes the Language System, which does semantic and syntactic checking on the C++ input program and translates the C++ program to C language. The CC command then invokes the C compiler on your machine to compile the resulting C program and run related processes such as linking function libraries.

Figure 1-1 shows the operation of the CC command and the processes it invokes:

Figure 1-1: Operation of the CC Command



The C++ Language System can run on most UNIX systems with a C compiler that supports the following features:

- long variable names (of at least 31 characters)
- structures as arguments to functions and return values from functions

See "Installation Procedures" for detailed prerequisites and information on porting.

New Features Introduced in Release 3.0

Release 3.0 is a release of the C++ Language System, which is source– and link–compatible with Release 2.0 and Release 2.1. Release 3.0 provides the following new or enhanced features:

- The major feature for the release is Template classes and functions. For a definition and description of how to use this feature, please refer to Stroustrup, "Parameterized Types for C++" in the *Selected Readings* as well as Chapter 14 of the *Reference Manual*, by Margaret Ellis and Bjarne Stroustrup (Addison-Wesley, 1990). This implementation conforms to the draft submitted to and preliminarily accepted by the ANSI C++ standards committee. However, users should note that there continues to be much discussion in the ANSI committee about the precise details of syntax and semantics regarding templates. While we do not expect major, incompatible changes in the definition of templates, it is likely that various refinements and extensions to the feature will be made in the course of the standardization activity. Users should be aware that any such refinements and extensions will be reflected in future releases of the AT&T USL C++ Language System.

  The Templates implementation is based on work originally done at Object Design Inc., in which they implemented template classes based on Stroustrup's initial design. We have licensed this initial templates implementation from Object Design and evolved it to include function templates, and have extended the class implementation to provide support for various language features such as friends and static members.
- Release 3.0 completes the implementation of true nested scopes introduced in Release 2.1. The transition model is no longer supported. Code that compiled warning-free under Release 2.1 will correctly reflect the new nested semantics.
- Release 3.0 begins a phased approach to improving the architecture of cfront. This release includes reworking of the front end symbol table, type checking, function matching, operator overloading and user-defined conversions.
- Release 3.0 implements various Release 2.1 *Reference Manual* upgrades, including allowing constructors in which all parameters have default arguments to be used as the default constructor in initializing arrays, overloaded prefix and postfix increment and decrement, extension of dominance to data, and use of constructor syntax for built-in types and protected derivations.
- Release 3.0 treats as errors most anachronisms which were warned about by default in Release 2.1. Those that were +w only warnings are generally being warned about by default in Release 3.0 and will be disabled in the release following 3.0.

Additional information about these improvements is provided in Chapter 4.

Hardware

The C++ Language System Release 3.0 can be installed on the following machines:

- AT&T WE 32000-based 3B2 Series Computers
- AT&T 6386 WGS
- DEC VAX line of Computers (including VAX BSD machines)
- SUN 2, SUN 3, and SUN 4 Workstations

The Language System has also been successfully ported to other machines, including:

- Motorola 68000-based Apollo and HP workstations
- Amdahl UTS Computer
- Intel 80286 large model and 80386-based machines
- Hewlett-Packard 9000 series 800 and series 300 HP-PA based machines
- IBM RT Personal Computer
- Data General MV Computers running AOS/VS and DG/UX
- MIPS machines

The C++ Language System can also be ported to other machines not on this list. Porting to machines besides the AT&T 3B series, AT&T 6386 WGS, DEC VAX line of computers, and SUN 2/3/4 workstations requires that you have access to an AT&T 3B series, AT&T 6386 WGS, DEC VAX, or SUN 2/3/4 computer, or that you have access to an existing working C++ Language System. For information about porting, see Chapter 3, under "Porting the C++ Language System."

2

Contents of the Release

This chapter intentionally removed.

3 Installing the Compiler

This chapter intentionally removed.

For instructions on installing HP C++, see the *HP C++ Release Notes* you received with HP C++.

4 Compatibility

Overview

This chapter describes compatibility issues that pertain to both Release 2.1 and Release 3.0. If you are currently using Release 2.1 and want to know about upgrading to Release 3.0, you can read the section "Upgrading from Release 2.1 to Release 3.0". If you are currently using Release 2.0, you should begin with "Upgrading from Release 2.0 to Release 2.1." In either case you should also read the last section, "Future Compatibility Issues," to learn about changes that will occur in the next major release of the C++ Language System.

Upgrading from Release 2.1 to Release 3.0

This section describes differences between Release 2.1 and Release 3.0.

This section provides information on the following topics:

- Header Files
- New Features
- Language Related Fixes

Recompilation of Release 2.1 Code

Code which compiled warning-free under Release 2.1 will not need to be recompiled. Code which uses nested types and which was not upgraded to use the transition model of Release 2.1 will need to be recompiled:

```
struct A {
      struct B {
            void f();
      };
};

typedef A::B T;

void T::foo() {};   // encoded as f__1BFv in 2.1
                    // encoded as f__Q2_1A1BFv in 3.0
```

However, code which used the new nesting semantics in Release 2.1 will continue to link correctly:

```
struct B {};        // force new nesting semantics
struct A {
      struct B {
            void f();
      };
};

typedef A::B T;

void T::f() {};             // encoded as f__Q2_1A1BFv in 2.1 and 3.0
```

Refer to the section below on Nested Types for further information.

Header Files

The `os` makefile variable has been updated to accomodate SunOS 4.1and UNIX System V Release 4. See the discussion of the `os` makefile variable in Section 3 *Installing the Compiler* in this manual for further information.

New Features

The major new feature for the release is the implementation of Templates. Various new features introduced in the Release 2.1 Reference Manual have also been implemented.

Templates

The major enhancement in this realease is the implementation of Templates. Both template classes and functions are supported. Automatic instantiation of templates is also provided. For a description of the feature and its uses, see Chapter 14 of the C++ *Language System Product Reference Manual,* and "Parameterized Types for C++", B. Stroustrup, in the *Selected Readings* manual. For information about support for automatic instantiation, refer to the *Selected Readings* Chapter 7, "Template Instantiation in C++ Release 3.0, Overview", G. McCluskey and R. B. Murray, which presents an overview and technical rationale for the instantiation mechanism and Chapter 8, "Template Instantiation, Users Guide", G. McCluskey, which presents various examples of use of the automated support for instantiations.

This implementation conforms to the draft submitted to and preliminarily accepted by the ANSI C++ standards committee. However, users should note that there continues to be much discussion in the ANSI committee about the precise details of syntax and semantics regarding templates. While we do not expect major, incompatible changes in the definition of templates, it is likely that various refinements and extensions to the feature will be made in the course of the standardization activity. Users should be aware that any such refinements and extensions will be reflected in future releases of the AT&T USL C++ Language System.

Implementation of Template Function Matching

During Release 3.0 beta testing, the restrictive function matching rules specified in the *Reference Manual* were found to be too restrictive for practical use. We have, therefore, implemented extensions to the strict function matching rules in the *Reference Manual.* It is likely that the ANSI definition will at least be relaxed to allow these extensions and may extend the definition to encompass full function matching. This is currently an active topic of discussion within the ANSI committee. In the meantime, we have made the smallest set of extensions we found feasible.

The first extension allows the consideration of trivial conversions when searching for an exact match. This implies that for a template function declared as follows:

```
template <class T> max( const T*, int );
```

the following call is legal in the Release 3.0 implementation:

```
int ia[10] = { ... };

// error in the Reference Manual
// accepted by 3.0
int best = max( ia, 10 );
```

The second extension allows the conversion of derived classes to public base classes in calls of template functions. This is necessary to ensure that template functions support object-oriented programming. For example, under the strict rules the following calls of function `print_vector()` fail:

```
template <class T> void print_vector(const Vector<T>&);

template <class T>
class BoundedVector : public Vector<T> { ... };

template <class T>
class SortedVector : public Vector<T> { ... };

BoundedVector<int> bv;
SortedVector<int> sv;

print_vector(bv);   // error in Reference Manual
                    // accepted by 3.0

print_vector(sv);   // error in Reference Manual
                    // accepted by 3.0
```

and separate print functions for each class derived from `Vector<T>` must be written. Permitting the conversions of `BoundedVector<int>` and `SortedVector<int>` to `Vector<int>` allows the use of the polymorphic `print_vector()` function.

These extensions are designed to be interim solutions until the ANSI committee votes on a full resolution to the template function matching issue.

Template Instantiation Support

An important aspect of the Release 3.0 implementation is support for automatic instantiation of template class and template function references. The Release 3.0 implementation provides an instantiation mechanism designed to free the programmer from direct manual intervention. Manual overrides for complicated systems are provided to customize and tailor instantiation support for specialized applications.

As discussed above, papers describing template instantiation are included in the *Selected Readings* with this release. These papers make clear that some assumptions are made about coding style and conventions:

- A class or function template is declared in a `.h` header. For a function template this declaration looks like a forward function declaration:

  ```
  template <class T> void f(T);
  ```

  The template `.h` header should include headers, with multiple-include guards, for "unbound", i.e., non-template-arg types that it uses.

- A class or function template is implemented in a `.c` header.

- Template arguments of non-fundamental type are declared in `.h` header files. These files should be self-contained, i.e., include other files they need using multiple-include guards.

Here is a simple example to get started with:

```
// Sample.h
template <class T> class Sample {
        char* p;
public:
        Sample(char* s) : p(s) {}
        char* get();
        char* get2() {return T::f();}
};

// Sample.c
template <class T> char* Sample<T>::get()
{
        return p;
}

// A.h
struct A {
        static char* f() {return " ";}
};

// application
#include <stdio.h>
#include "Sample.h"
#include "A.h"

Sample<A> a("Hello");

main()
{
        Sample<A> b("world");

        printf("%s%s%s0, a.get(), a.get2(), b.get());
}
```

This is a complicated way of printing "Hello world". To compile this example, you would create the various files noted above and say:

```
$ CC app.c
```

It is instructive to look in the directory `./ptrepository` after such a compile. There are three files there whose use is fully explained in the paper:

xxx.c	- the instantiation file
xxx.o	- the instantiation itself
xxx.cs	- the checksum used for dependency management

Nested Types

Release 3.0 also completes the implementation of true nested scopes introduced in Release 2.1. The transition model is no longer supported. Code that compiled warning free under Release 2.1 will correctly reflect the new nested semantics. Please note that code that generated warnings under Release 2.1 may produce results under complete nested semantics that differ from Release 2.0 behavior:

```
class A {
      class B {
            ...
      };
      ...
};

B bvar;

      // 2.1: warning: use  A:: to access nested  class type B  (anachronism)

      // 3.0: error: B bvar : B is not a type name
      //      error:  type expected for bvar
```

Support for deeply nested classes is also now provided:

```
class A {
      class B {
            class C {
                  ...
            };
            ...
      };
};
```

Reference to the inner class C is now possible:

```
A::B::C cvar;
```

Default Constructors

The Release 2.0 *Reference Manual* explicitly stated that a default constructor is a constructor with no formal parameters, thereby excluding constructors that can be called with no arguments by virtue of having default arguments. The Release 2.1 and Release 3.0 versions of the *Reference Manual* lift this restriction; the constructor in the example below is now considered a default constructor.

```
struct S {
      S(int = 0);
};
```

Release 2.1 does not conform to this rule. Instead, it adheres to the old definition of default constructor. Here are some examples:

```
S s1[2];              // legal, OK in 3.0, error in 2.1
S s2[2] = { 1 };      // legal, OK in 3.0, sorry in 2.1

struct X {
      S s[2];                 // legal, OK in 3.0, error in 2.1
};

void f() {
      S* p = new S[2];        // legal, OK in 3.0 and 2.1
}
```

Release 3.0 correctly conforms to this rule.

Explicit Type Conversions with Empty Initializers

The Release 2.1 and 3.0 versions of the *Reference Manual* allow you to specify an explicit type conversion with an empty initializer, as in the following examples:

```
int i = int();

struct Empty {};
Empty e = Empty();
```

Release 2.1 does not implement this capability and reports an error instead.

```
line 1: error: value missing in conversion to int
line 4: error: cannot make a Empty
```

Release 3.0 implements this capability.

Prefix and Postfix Increment and Decrement Operators

The Release 2.0 *Reference Manual* provided no way to distinguish user-defined prefix increment and decrement operators from postfix increment and decrement operators. The Release 2.1 and 3.0 versions of the *Reference Manual* specify a separate syntax for defining prefix and postfix increment and decrement operators. The prefix increment and decrement operators take one argument (the implicit `this` argument for a member function), whereas the postfix version takes two arguments (including the implicit `this` argument). For example,

```
struct S {
        operator++();          // 2.0: prefix or postfix
                                   // 2.1: prefix, but not implemented as such
                                   // 3.0: prefix, implemented as such
        operator++(int);           // 2.1: postfix ++, not implemented
                                   // 3.0: postfix ++, implemented
};
```

However, Release 2.1 does not recognize the new syntax. Use of the postfix form results in the following error message:

```
line 4: error:  S:: operator ++() takes no argument
```

Release 3.0 correctly handles these operators.

Extension of Dominance Rule to Objects

The Release 2.1 *Reference Manual* extended dominance to data and enumerators as well as functions. Release 2.1 did not implement this. Release 3.0 does:

```
enum E {a,b};
struct V {void f(); int x; E y;};
struct B: public virtual V {void f(); int x; E y;};
struct C: public virtual V{};

struct D: public B, public C {void g();};

void D::g() {
        x++;           // ambiguous in 2.0/2.1
                       // ok in 3.0, refers to B::x
        y = a; // ambiguous in 2.0/2.1
                       // ok in 3.0, refers to B::y
        f();           // ok in 2.0/2.1 and 3.0, refers to B::f
}
```

Protected Derivation

The Release 2.0 *Reference Manual* explicitly disallowed the use of `protected` as an access specifier for a base class. The Release 2.1 *Reference Manual* lifts this restriction. However, Release 2.1 does not implement the new behavior.

```
struct B {};
struct D : protected B {};// legal, but rejected by 2.1
                          // accepted by 3.0
```

Release 3.0 correctly implements the new behavior.

Exception Handling Syntax

Release 3.0 does not include an implementation of exception handling. However, the ANSI C++ committee has preliminarily accepted the exception handling scheme as described in Chapter 15 of *The Annotated C++ Reference Manual*. In Release 2.1, reserved words were added for exception handling. In Release 3.0, the likely syntax for exception handling has been incorporated into the grammar and a "sorry not implemented" message is generated for uses. Again, code that compiled warning free under Release 2.1 will continue to compile and execute correctly under Release 3.0. Please note that Release 2.1 code that compiled with warnings about use of reserved words may result in surprising error messages under Release 3.0:

```
int try;

        // 2.1: warning:  try is a future reserved keyword

        // 3.0: sorry, not implemented:  try
        //      error: syntax error
```

Language-Related Fixes

The focus of development for Release 3.0 has been to implement the Templates feature and to reengineer selected portions of the implementation. The reengineering focus has been on function matching, operator overloading, user-defined conversions, type checking and reworking the front end symbol table. We know of no bugs in the function matching or operator overloading and many of the scoping and name reuse bugs that existed in previous releases have been fixed. The reworking of type checking has uncovered previously existing bugs that are now fixed. Please note, some of these fixes may change the behavior of programs for which Release 2.0 or Release 2.1 incorrectly accepted illegal code or produced incorrect results.

Section numbers (§) following a heading identify the section of the Release 3.0 *Reference Manual* that describes the correct behavior.

Declarations in `for` Initializers (§6.5.3, 6.7)

The Release 2.0 *Reference Manual* stated that a `for` statement containing a declaration in its *for-init-statement* was not allowed to be the statement after an `if`, `else`, `switch`, `while`, `do`, or `for`. In other words, this code was illegal:

```
void f(int i) {
      if (i)
            for (int j = i; j; j--)          // error
                  ;
}
```

This restriction was an error not enforced by the Release 2.0 implementation, and the Release 2.1 *Reference Manual* omits it.

The Release 2.1 *Reference Manual*, however, does specify a related restriction: "An `auto` variable constructed under a condition is destroyed under that condition and cannot be accessed outside that condition."

Here is an example:

```
int g(int i) {
      if (i)
            for (int j = 5; j; j--)
                  ;
      return j;     // error
}
```

In the above code, `j` cannot be accessed at the point of the `return` statement because the `return` statement is outside the body of the `if` statement. According to the Release 2.1 *Reference Manual*, an error should be reported, but Release 2.1 quietly accepts this code. Release 3.0 correctly reports the error.

Enforcement of Return from Value-Returning Functions (§6.6.3)

In C++, unlike C, it is an error to fail to return a value from a value-returning function. See Section 6.6.3 of the *Reference Manual*. Earlier releases of the compiler warned about failure to return a value. For Release 3.0, these warnings are errors for all member functions and all function templates. For non-member functions, failure to return a value when a return type is explicitly specified is an error; warnings will continue to be generated for non-member functions that implicitly return ints. As with previous releases, we will continue to warn about failure to return from `main` only under `+w`.

```
main() {/*...*/};                 // no return from main
                                  // +w warning in 2.0, 2.1 and 3.0

f() { /*... */ };                 // no return, implicit return type
                                  // warning in 2.0, 2.1 and 3.0

int f2() { /*...*/ };             // no return, explicit return type
                                  // warning in 2.0, 2.1
                                  // error in 3.0

struct A {
      f() {/*...*/};              // no return, implicit return type
                                  // warning in 2.0, 2.1
                                  // error in 3.0

      int f2() {/*...*/}; // no return, explicit return type
                                  // warning in 2.0, 2.1
                                  // error in 3.0
};
```

`const` Typedefs (§7.1.6)

Previous releases failed to unwind `const` typedefs correctly:

```
typedef char *T;

const char *p;      // p is a pointer to a const char
const T cp;         // cp is a constant pointer to char
```

Previous releases incorrectly evaluated `cp` as a pointer to `const char`.

Scope of a Class Member's Initializer (§8.4)

The Release 2.1 *Reference Manual* states explicitly that an initializer for a static member is in the scope of the member's class. This rule was not explicitly given in the previous *Reference Manual*.

Release 2.1 does not apply this rule consistently. For example, in

```
const int a = 5;

struct X {
      static int a;
      static int b;
};

int X::a = 1;
int X::b = a;
```

the correct behavior is implemented: `X::b` is initialized with `X::a`.

However, default arguments for member functions are not resolved within the scope of the class. In the following code,

```
const int y = 2;

struct Y {
      static int y;
      static int f(int);
};

int Y::f(int i = y) { return i; }
```

Release 2.1 incorrectly determines that the default argument for `Y::f()` is global `y`, not `Y::y`.

Release 3.0 correctly resolves the argument.

Reference Initializers (§8.4.3)

The Release 2.0 *Reference Manual* allowed a reference to be initialized with a temporary, as in the following declaration:

```
int& r = 5;
```

However, the Release 2.1 *Reference Manual* has tightened the rules for reference initializations so that only `const` references may legally be initialized with non-lvalues. This means that, instead of the previous declaration, you must use the following:

```
const int& cr = 5;
```

The Release 2.0 C++ Language System already treated temporary initializers for non-`const` reference initializations at global scope as errors, although it allowed them at local scope. To provide a smooth transition to the more restrictive rules, Release 2.1 issues an anachronism warning, under control of the `+w` option, for non-`const` reference initializations that were accepted by Release 2.0 but are now illegal.

Here are some examples:

```
int& r1 = 5;        // illegal, error in 2.0, 2.1 and  3.0

struct A { A(int); ~A(); };
A& a1 = 5;                  // illegal, sorry in 2.0, error in 2.1, 3.0
const A& a2 = 5;            // legal

int& f1();
int& r2 = f1();             // ok, 'f()' returns an lvalue

const int& r3 = 5;  // ok, 'r3' is 'const int&'

int f2(int&);
int j = f2(5);          // illegal, error in 2.0 and 2.1

void x() {
      int& r1 = 0; // illegal, 2.1 warns under +w
                        // illegal, 3.0 warns by default
      A& a1 = 5;        // illegal, 2.1 warns under +w
                        // illegal, 3.0 warns by default
      const A& a2 = 5;  // legal, accepted by 2.0 and 2.1
      int j = f2(5);    // illegal, 2.0 and 2.1 warn under +w
                        // illegal, 3.0 warns by default
}


struct S1 {};
struct S2 {
      operator S1();
};

void f3(S1&);
void y(S2 s2) {
      f3(s2);               // illegal, 2.0 and 2.1 warn under +w
                    //illegal, 3.0 warns by default
}
```

Release 3.0 issues an unconditional warning, or an error if the +p option is in effect.

The anachronism warnings turn into errors if the +p option is specified to the CC command.

Calls to Non-`const` Member Functions from `const` Objects (§9.3.1)

Calling a non-`const` member function on a `const` object has been illegal since Release 2.0. However, to ease transition to this new rule, calling a non-`const` member function on a `const` object was flagged with a warning in Release 2.0 and Release 2.1. This type of call is an error in Release 3.0.

The obvious example of the effect of this change is the simple changing of a warning to an error as in the following case:

```
struct A {
    A();
    void foo();
};
const A a;
a.foo();        // a warning in 2.0 and 2.1
                // an error in 3.0
```

However, this change may also cause more subtle changes of behavior in code using function matching, operator overloading, or conversion functions. For example, a non-`const` member function is now eliminated from consideration in a call to an overloaded member function using a const object. For example:

```
struct A {
    A();
    void foo(int);         // #1
    void foo(char) const; // #2
    void foo(const A*);          // #3
};
const A a;
a.foo(1);       // used to call #1 with warning
                // now will call #2
a.foo(&a);      // used to call #3 with warning
                // now flagged as no match error
```

Similarly, non-`const` user-defined operators are not considered for calls with `const` objects, and no non-`const` conversion operators will be applied to `const` objects.

An example with conversion operators:

```
class B {
public:
      B();
      operator int();
};

const B b;
int i = b;      // error in 3.0
```

New errors that occur as a result of all usable functions being non-const should issue messages that include that information. For example, the program above gives the following error in Release 3.0:

```
"prog.c", line 8: error: bad initializer type const B for i (int expected)
(no usable const conversion)
```

Enforcement of `const` in `const` Member Functions (§9.3.1)

As with calls to non-`const` member functions from `const` objects, the enforcement of `const` within `const` member functions was introduced via warnings in Release 2.0 and Release 2.1. In Release 3.0, the `const` rules are strictly enforced. The release correctly reports errors for assignment to data members or calls to non-`const` member functions from within a `const` member function. It is also illegal for `const` member functions to return non-`const` references to a data member if the member is a class object. If the data member being returned is a built-in type, however, Release 3.0 still incorrectly reports this with just a warning.

```
struct B{ };

struct A {
        int i;
        B b;

        int& f() {return i;};           // ok, non-const member

        void f1(int j) const {
                i = j;          // warning in 2.0/2.1
                                        // error in 3.0

                i = f();                // warning in 2.0/2.1
                                        // error in 3.0
        }

        int& f2() const {return i;}     // warning in 2.0/2.1
                                        // error in 3.0

        B& f3() const {return b;} // warning in 2.0/2.1/3.0
};
```

Static Data Members of Local Classes (§9.4)

The Release 2.1 *Reference Manual* states that static data members are not allowed for local classes. Previously, a local class could have a static data member only if no explicit initialization was required.

Release 2.1 does not enforce the new restriction properly. If a static data member of a local class is declared but never used, a warning is reported but the program links successfully.

```
int main() {
        struct S {
                static int i;
        };
        // ...
        return 0;
}
```

```
line 2: warning: static member S::i in local class S (anachronism)
```

Release 3.0 enforces this restriction, and correctly reports an error.

Access Specifiers in Unions (§11)

The Release 2.1 *Reference Manual* allows access specifiers in unions. Formerly, these were forbidden.

```
union U {
public:                     // legal
        U();
        int i;
private:                    // legal
        double d;
protected:                  // legal
        float f;
};

U u;
float f = u.f;              // protection violation
```

Release 2.1 accepts the definition of `U` shown above but does not report the protection violation.

Release 3.0 correctly flags the protection violation.

Access to Static Members of Private Base Classes (§11.2)

The Release 2.1 *Reference Manual* states that a private derivation of a base class does not restrict access to the static members of the base class. Without this rule, a member function would have less access to a base class's static members than a global function.

Release 2.1 does not implement this rule consistently. For access to a static member of an immediate base class, some illegal accesses are not reported:

```
struct B {
      static void f();
};

struct D : private B {}
struct E : private D {
      void g() {
            f();                // illegal, reported by 2.1 and 3.0
            this->f();          // illegal, reported by 2.1 and 3.0
            B::f();             // legal, OK in 3.0, rejected by 2.1
      }
};
```

In the above code, the calls `f()` and `this->f()` are illegal because they refer to `f()` via the `this` pointer, and thus the access protection for `private` members is applied. The call `B::f()` is legal because it refers to `f()` directly, just as a global function could refer to `B::f()`.

Release 3.0 enforces the rule consistently. If multi-level derivation is involved, both Releases 2.0 and 2.1 are overly conservative; they report an error for `X::f()` even though it is legal.

```
struct X {
        static void f();
};
struct Y : private X {};
struct Z : public Y {
        void g() {
                f();            // illegal, error in 2.0, 2.1 and 3.0
                this->f();      // illegal, error in 2.0, 2.1 and 3.0
                X::f();         // legal, error in 2.0 and 2.1
        }
};
```

Scope of Friend Functions (§11.4, 9.7)

The Release 2.1 *Reference Manual* states that a `friend` function defined within a class declaration is in the lexical scope of that class, just like a member function.

In general, Release 2.1 does not implement this rule. Consider the following example:

```
extern int s;
extern int e;

struct S {
      static int s;
      enum { e = 5 };
      friend f() { return e; }  // which 'e'?
      friend void g(int = s) { };      // which 's'?
};
```

According to the Release 2.1 *Reference Manual*, `f()` returns `S::e` and the default argument for `g()` is `S::s`. Instead, both Release 2.0 and 2.1 incorrectly resolve these names to `::e` and `::s` respectively.

Release 3.0 resolves these names correctly.

Constructor and Destructor Declarations (§12.1, §12.4, §9.3.1,)

The Release 2.1 *Reference Manual* specifies that constructors and destructors cannot be declared `const`, `volatile`, or `static`. Release 2.1 correctly reports an error for constructors and destructors that are declared `static`, but it incorrectly allows constructors and destructors to be declared `const`. Release 2.1 does not implement `volatile` member functions at all; these are rejected with a "not implemented" message.

```
struct S {
      static S();            // illegal, error in 2.0, 2.1 and 3.0
      static ~S();           // illegal, error in 2.0, 2.1 and 3.0
};

struct T {
      T() const;             // illegal, but accepted by 2.1
                               // rejected by 3.0
      ~T() const;            // illegal, but accepted by 2.1
                               // rejected by 3.0
      T(char*) volatile;     // illegal, sorry in 2.1
                               // rejected by 3.0
};
```

Release 3.0 correctly reports these errors.

Destructors for Built-In Types (§12.4,)

The Release 2.1 *Reference Manual* allows explicit destructor calls for any built-in type, as in the example below. However, Release 2.1 does not implement this syntax.

```
void f(int* p) {
      p->int::~int();         // legal, but error in 2.1
                                // legal, handled properly in 3.0
};
```

Release 3.0 correctly implements this syntax.

Delete Operator (§12.5)

The Release 2.1 *Reference Manual* tightens the rules for the `delete` operator. Only one `operator delete()` may be declared per class, and the global `operator delete()` may not be overloaded. Release 2.1 does not enforce these restrictions.

For example, the second declaration of the `delete` operator in each scope below is illegal, but the code is accepted by both Release 2.0 and 2.1.

```
typedef unsigned int size_t;

void operator delete(void*);
void operator delete(const void*);          // error, correctly reported in 3.0

struct S {
      void* operator new(size_t);
      void* operator new(size_t, void*);
      void operator delete(void*);
      void operator delete(void*, size_t);  // error, correctly reported in 3.0
};
```

Release 3.0 correctly reports these errors.

Argument Matching Rules (§13.2,)

Several details about the function matching rules have changed.

- In the Release 2.0 *Reference Manual* there was a rule that a call needing only standard conversions is preferred over one requiring user-defined conversions. This rule has been eliminated in the Release 2.1 *Reference Manual* and the new semantics have been implemented in Release 2.1. For example,

```
struct Complex { Complex(double); };
void f2(int, Complex);
void f2(double, double);

void y2() {
      f2(3, 4);      // ambiguous
}
```

For this code, Release 2.1 and 3.0 correctly report an ambiguity.

- The second function matching change involves the treatment of arguments of type `T` that require temporaries. The Release 2.0 *Reference Manual* specified that a match with conversions requiring temporaries was a legal match. So, for example, the call to `f3(char&)` in the following code was legal and was accepted by Release 2.0:

```
void f3(char&);
void x3() {
      f3('c');       // illegal, 2.1 warns under +w
                     // illegal, 3.0 warns by default
}
```

  Furthermore, since standard conversions were preferred to conversions requiring temporaries, the *Reference Manual* specified that the call to `f4()` below would be resolved to `f4(int)`. Instead, Release 2.0 resolved it to `f4(char&)`:

```
void f4(int);
void f4(char&);
void x4() {
      f4('c');       // illegal, 2.1 warns under +w
                     // illegal, 3.0 warns by default
}
```

  Under the new rules, the calls to `f3()` and `f4()` are in error because a non-`const` reference cannot be initialized with a non-lvalue (see §8.4.3). However, Release 2.1 and 3.0 allow this behavior, with warnings, to provide the opportunity to migrate old code.

Release 3.0 correctly warns by default in both case. Release 2.1 warns under +w.

Improved Operator Overloading (§13.4)

Operator overloading and the resolution of operator expressions has been more clearly specified for Release 3.0, notably in the area of choosing between user-defined operators and built-in operators using conversions to basic types. For instance, given the following class definition:

```
class Foo {
public:
        operator int();
     int operator+(const Foo&,int);
};
```

and an object of class `Foo`, `foo`, the expression `foo + 1` could be resolved two ways. It could be resolved as `operator+(foo,1)` by calling the user-defined + operator, or as operator `int(foo) + 1` by using the built-in + operator on integers after applying the user-defined conversion to `int`.

For Release 3.0, the operator overloading algorithm has been updated to match the function matching algorithm. Therefore, argument matching is used to compare built-in operators to user-defined operators.

The only exceptions to this rule are operators which MUST be defined as members, i.e., `operator=()`, `operator[]`, `operator->()`, `operator()()`. For expressions involving these operators, the user-defined version of the operator is always preferred.

The effect of this clarification is that some expressions involving operators which used to call a user-defined operator will now be ambiguous. Other expressions which used to give an ambiguity error will now be resolved. For example,

```
class String {
public:
    String(char);
    friend String operator+(String&,char);
};

class MyClass {
public:
    operator int();
    friend int operator+(MyClass&,int);
    int operator[](unsigned int);
};

main()
{
    MyClass a;
    int i;

    i = a + 3;      // 1: used to call operator+(MyClass&,int);
                    //    still does
    i = a + 3.2;    // 2: used to call operator+(MyClass&,int);
                    //    now ambiguous
    i = a[3];       // 3: used to call operator[](unsigned int);
                    //    still does
    i = 3 + a;      // 4: used to be ambiguous
                    //    now calls built-in +
}
```

In call 1, Release 3.0 uses argument matching and chooses the user-defined operator. The best match on the first operand is the user-defined `operator+()`; the best matches on the second operand are both the user-defined `operator+()` and the built-in `operator+()` on integers. Thus, the intersection of best match functions is the user-defined `operator+()`.

Changing the right operand to a double makes call 2 ambiguous when using argument matching because the best match on the second operand will now be the built-in `operator+()` on doubles.

Call 3 still calls the user-defined `operator+()` because the user-defined version of `operator[]` is always preferred, since it must be defined as a member.

The last call (4) was ambiguous in pre-Release 3.0 versions of C++ because the call of the built-in `operator+()` on integers conflicted with `operator+(String&,char)`. Using argument matching, the call resolves to the built-in `operator+()` as the user would expect.

Miscellaneous Fixes & Enhancements

- Classes with destructors are now permitted in `||` and `&&` expressions.
- The limit on the size of inlines has been increased so that larger inline functions should now be laid down inline.
- The number of nested include files that cfront can handle has been made dynamic. The limit in Release 2.0/2.1 had been 127. Note that, of course, local *cpps* may vary in the limit they can process.
- Significant improvements have been made and extensive testing has been performed on the `+a1` (ANSI) option.
- Error messages for ambiguous function calls have been enhanced. The error message now lists the set of overloaded functions which were equivalently good.
- All known line numbering bugs are fixed.

Return Value Optimization

Release 3.0 supports a return value optimization which may avoid the copying of potentially large data structures which are returned from functions.

For instance, given the following class definition and function declaration:

```
class T {
        ...
public:
        T(const T&);
};

T foo();
```

An object of class T may be initialized with the return value of `foo()` as follows:

```
        T x = foo();
```

Such a function, `foo()`, will often have a definition something like the following:

```
T foo()
{
        T result;
        // do stuff to result
        return result;
}
```

This means that in order to do the above initialization, a copy will be done of `result` into `x`. If instead the function and the initialization had been written to look as follows:

```
void foo(T& result)
{
        // construct result
        // do stuff to result
        return;
}

T x;
foo(x);
```

the copy would be avoided altogether while achieving the same results.

Under certain conditions, cfront will now perform a transformation from the original, more natural, definition of `foo()` to the second definition automatically, thus avoiding the copy on the return.

This return value optimization is done under the following conditions:

- The function returns an object of type `T`, where `T` has a copy constructor, and
- The function creates a local variable of type `T`, say `result`, which is declared and returned at the top block of the function.
- The function does not return anything but `result`, from anywhere in the function between the declaration and return of `result`.

This optimization can eliminate the non-intuitive tricks that programmers often use to avoid copying of large objects on returns.

Upgrading from Release 2.0 to Release 2.1

Release 2.1 of the C++ Language System is source compatible with Release 2.0. That is, a legal C++ program that compiled and executed correctly with Release 2.0 will continue to compile and execute correctly with Release 2.1.

In addition, Release 2.1 is link compatible with Release 2.0. This means that libraries that were compiled using Release 2.0 do not need to be recompiled before linking with programs compiled with Release 2.1.

This section lists changes in Release 2.1. Most of these changes are bug fixes that have been made so that Release 2.1 more accurately reflects the definition of the C++ language given in the *Reference Manual.*

This section covers the following topics:

- "Building the Compiler" — tells you information you must know before installing the C++ compiler
- "Header Files" — tells you about changes to the header files in Release 2.1
- "Changes to the `CC` Command" — tells you about changes in options to the `CC` command, macro name changes, and other changes in functionality
- "Language-Related Fixes" — tells you about fixes to the compiler that enforce language rules more accurately
- "*Reference Manual* Changes" — describes differences between the Release 2.0 *Reference Manual* and the Release 2.1 *Reference Manual*.
- "New Warning Messages" — lists warning messages that have been added for Release 2.1
- "Library Changes" — describes changes to the libraries supplied with Release 2.1

Recompilation of Release 2.0 Code Not Required

Code compiled using Release 2.0 does *not* need to be recompiled.

You might, however, want to recompile your old code using Release 2.1 anyway, as Release 2.1 enforces some language rules that were not enforced by Release 2.0. If you recompile your code, you will find out if it makes use of constructs that are illegal.

Building the Compiler

`szal` Output Format

The format of the output of the `szal` program has been improved for Release 2.1. The new output is in the same format as the entries in the `src/size.h` file. This change makes it easier to add new systems to `src/size.h`.

For example, the commands:

```
cc -o szal szal.c
szal
```

when executed on an AT&T 3B2 computer yield the following output:

```
#define DBI_IN_WORD 32
#define DBI_IN_BYTE 8
#define DSZ_CHAR 1
#define DAL_CHAR 1
#define DSZ_SHORT 2
#define DAL_SHORT 2
#define DSZ_INT 4
#define DAL_INT 4
#define DSZ_LONG 4
#define DAL_LONG 4
#define DSZ_FLOAT 4
#define DAL_FLOAT 4
#define DSZ_DOUBLE 8
#define DAL_DOUBLE 4
#define DSZ_LDOUBLE 8
#define DAL_LDOUBLE 4
#define DSZ_STRUCT 4
#define DAL_STRUCT 4
#define DSZ_WORD 4
#define DSZ_WPTR 4
#define DAL_WPTR 4
#define DSZ_BPTR 4
#define DAL_BPTR 4
#define DLARGEST_INT "2147483647"
#define DF_SENSITIVE 0
#define DF_OPTIMIZED 1
```

PLUSA Makefile Variable

You can now use the PLUSA variable in the makefile to set the +a CC command option to the desired default setting before executing the build procedure. The build procedure will then generate a CC command that will use the specified setting for +a as the default. The default setting can, of course, be overridden on the command line when invoking the CC command. The default value for PLUSA in the makefile is +a0.

`patch`

The file `BSDpatch.c` has been modified so that `patch` works under BSD Release 4.3 running on DEC VAX computers.

Header Files

Header File Bug Fixes

Bug fixes made to header files for Release 2.1 fall into several categories:

- missing prototypes were added,
- prototypes for functions specified by the ANSI C standard were updated to match the prototypes in the ANSI specification,
- some headers that were missing for certain platforms have been added.

`stdlib.h` and `libc.h`

In Release 2.0, `stdlib.h` and `libc.h` were similar, but not identical. In Release 2.1, they are identical. `stdlib.h` is the ANSI C–specified header file used to declare many standard C library functions previously undeclared in C header files. `libc.h` is retained for compatibility with previous releases of the C++ Language System.

`curses.h` Proto-Headers Reorganized

Because of the great differences between various versions of `curses.h`, the proto-header for `curses.h` has been divided into three separate files: one for SVR2 (`proto-headers/curses.svr2`), one for SVR3 (`proto-headers/curses.svr3`), and one for all the other systems supported (`proto-headers/curses.h`).

In addition, the `curses.h` header for SVR3 has been upgraded to SVR3.2.

Changes to the `CC` Command

`a.out` File Permissions

Under Release 2.0 the `CC` command left the resulting `a.out` file with executable permission even if the `munch` or `patch` step of the compilation process failed. The Release 2.1 `CC` command does not make the `a.out` file executable if the `patch` or `munch` step of the process fails.

+L Option

The +L option had no effect in Release 2.0 because the compiler always generates source line information using the format #line %d. The +L option has therefore been removed from the CC man page for Release 2.1.

-Fc Option

The -F and -Fc options produce identical results in Release 2.0 and Release 2.1. They both run only the preprocessor and the compiler on the source files and send the generated C source code to the standard output. Therefore the -Fc option has been dropped as a separate option on the CC man page for Release 2.1, although it is still implemented.

Position-Independent Options

Options such as -Y, +a[01], -E, -F, -C, -P, -H, -S, -c, -I, -D, -U and -g are no longer position-dependent on the command line. Instead, they apply to all files specified on the command line. For example, under Release 2.1 the command:

```
CC foo.c -DDEBUG bar.c
```

defines the macro DEBUG for both foo.c and bar.c, whereas in Release 2.0 DEBUG was only defined for bar.c.

Not all options have been made position-independent, however. The +d, +p, and +w options are still position-dependent, as they were in Release 2.0. These options affect only those files named after the option is specified; the files named before the option are not affected. For example, the following command causes the +w option to be applied only to y.c, and not to x.c.

```
CC x.c +w y.c
```

The +e[01] options are also still position-dependent. Each +e option applies to all files listed before the next +e option is encountered. For example, in the case below +e0 is applied to the files x.c and y.c, whereas +e1 is applied to z.c:

```
CC +e0 x.c y.c +e1 z.c
```

The +a option specifies whether "Classic" C code or ANSI C-conforming code should be produced. Because the CC command invokes a single C compiler, it is assumed that only one setting of the +a option is appropriate. If multiple +a[01] options are specified on the command line, the last option is the one actually used, and it is applied to all files. For example, the following command causes the +a1 option to be applied to x.c, y.c, and z.c.

```
CC x.c +a0 y.c +a1 z.c
```

Partial Compilation Options

If the options specified to the CC command contain a combination of the -P (run only the preprocessor step), -S (stop after creating the assembler input), and -c (compile but do not link) options, the option referring to the earliest stage of compilation is chosen and the others are ignored. For example, the following invocation causes the CC command to perform the preprocessing step *only* on the three files:

```
CC x.c -P y.c -S z.c
```

Virtual Table Optimization Improved

Release 2.1 provides the same virtual table strategy that was provided by Release 2.0.

Release 2.1 provides a further improvement on the treatment of virtual tables. Under Release 2.0, each virtual table had a companion pointer variable, which was used to hold housekeeping information necessary for the virtual table optimization. Under Release 2.1 these pointers are allocated in an array, rather than one per virtual table, so that only one symbol table entry is required in the generated object file. This change reduces the symbol table size (but not the runtime data size) of programs compiled with Release 2.1.

The new optimization is link compatible with Release 2.0.

More Debugging Information Generated Under the -g Option

Under Release 2.0, the -g option, which causes additional debugging information to be generated, was only passed to the underlying C compiler; it did not affect the behavior of the compiler itself. Under Release 2.1, however, the -g option also affects the behavior of cfront. If -g is specified, the compiler produces C code for *every* declaration in the compilation, rather than only for those declarations that are actually needed or used. This additional information allows for easier debugging, but it also increases the size of the object file because the symbol table is larger.

Warnings about Inline Functions Issued under the +w Option

Several customers have noted that Release 2.0 did not treat consistently inline functions that cannot be successfully inlined. Release 2.1 addresses this problem by providing more consistent information about whether inline functions are actually being inlined.

There are several cases:

- If an inline function is seen for which cfront cannot generate inline code, and cfront cannot recover from the error condition, a "not implemented" message is reported. (The "not implemented" messages are described in Appendix D of the Release 2.1 *Reference Manual*.)
- If an inline function is seen which cannot be inlined for some other reason (e.g., it is too long or it is a virtual function), and cfront can recover, the function will not be inlined and a warning message will be issued if the +w option is specified.
- If a *call* to an inline function is seen and, because of the characteristics of the call site, the particular call cannot be generated inline, a warning message will be issued if the +w option is specified.
- If the address of an inline function is taken, a warning message will be issued if the +w option is specified.

Because the `inline` keyword is a "hint" to the compiler, and because the C++ Language System issues warnings unconditionally only about constructs that are almost certainly serious problems, warnings about inlines are issued only if the +w option is specified.

The following code illustrates the treatment of inlines:

```
inline int f(int) { return i; }

int g(int i) { return f(i); }

inline void h() {
        static int i = 5;
        // ...
}

struct S {
        virtual void f() {}
};
```

If you compile this code using `CC +w` you get the following output:

```
line 5: sorry, not implemented: cannot expand inline function with static i
line 10: warning: virtual function S::f() cannot be inlined
line 12: warning: out-of-line copy of  S::f() created
```

For more information about inline functions, see Chapter 8 of the *Selected Readings*.

Language-Related Fixes

This section describes bug fixes in Release 2.1 that may break some code that used to be accepted, but should never have been accepted. Section numbers (§) following a heading identify the section of the Release 2.1 *Reference Manual* that describes the correct behavior.

Implicit Conversions of Pointers to Members (§4.8)

Release 2.0 incorrectly permitted several kinds of implicit conversions involving pointers to members.

- Implicit conversions between pointers to members of unrelated types were permitted:

```
struct X { int i; };
struct Y { int i; };
int X::*pmXi = &Y::i;      // error
```

- Conversions from pointers to objects to pointers to members were also allowed:

```
struct Z { int i; };
int i;
int Z::*pmZi = &i;  // error
```

- Finally, conversion from a pointer to member of a base class to a pointer to member of one of its derived classes was permitted:

```
struct B { int i; };
struct D : B { int i; };
int B::*pmBi = &D::i;      // error
```

Release 2.1 correctly enforces these rules and reports an error in these cases.

Casts of Pointer Types (§5.4)

The *Reference Manual* states that a pointer may be explicitly converted to any integral type large enough to hold it. If the integral type is not large enough, the conversion is illegal. Release 2.1 enforces this rule; Release 2.0 did not.

```
char *p;
unsigned short us = (unsigned short) p;       // error
unsigned short us1 = (unsigned short) (int) p;       // ok
```

Better Enforcement of `const` (§7.1.6)

Release 2.0 did not always realize that a member of a `const` object is itself a `const`. For example, the assignment to `b.a.i` in the code below was permitted, even though `b` is `const` and therefore its members are also `const`.

```
struct A {
        int i;
};
struct B {
        A a;
        B();
};
void f() {
        const B b;
        b.a.i = 5; // error
}
```

Release 2.1 issues the following message:

```
line 10: error: assignment to member A::i of const B
```

Initialization of `const` Class Objects (§7.1.6)

The *Reference Manual* states that all `const` objects not explicitly declared to be `extern` must be initialized. Although Release 2.0 enforced this rule for built-in types, it did not require explicit initializations for `const` class objects, such as `a1` in the example below:

```
struct A { int a; };
struct B { B(); };
const A a1;               // error, no initializer
const A a2 = { 1 }; // ok, explicit initialization
const B b1;               // ok, implicit initialization by constructor
A a3;                     // ok, non-const
```

Release 2.1 generates the following error for this code:

```
line 3: error: uninitialized const ::a1
```

Linkage Specifications (§7.4)

Release 2.0 did not enforce all the constraints on the use of linkage specifications. For example, it allowed a function declaration without a linkage specification to precede one with a linkage specification. This error is flagged by Release 2.1.

```
int f();
extern "C" int f(); // error
```

```
line 2: error: inconsistent linkage specifications for f()
```

Local Variables in Default Arguments (§8.2.6, §10.4)

The *Reference Manual* forbids the use of local variables in default argument expressions. For example,

```
void f(int i) {
      void g(int = i);
      // ...
}
```

causes Release 2.1 to report the following error:

```
line 2: error: local i used as default argument
```

This error was not reported by Release 2.0.

Braced Initializers for Aggregates (§8.4.1)

The *Reference Manual* states that braced initializers may be used to initialize aggregates, which by definition cannot have private or protected members, constructors, base classes, or virtual functions. Release 2.0 did not enforce this rule for classes with private members, or for aggregate members that were not themselves aggregates. For example, Release 2.0 incorrectly allowed both initializations shown below.

```
class A {
        int a;
};

struct B {
        A obj;
};
A a = { 5 }; // error
B b = { 5 }; // error
```

Release 2.1 correctly generates errors for the initializations of a and b:

```
line 9: error: cannot initialize ::a with initializer list
line 10: error: cannot initialize ::b with initializer list
```

const Violations in const Member Functions (§9.3.1)

Release 2.0 did not consistently detect const violations in const member functions. For example, the following code is illegal because the value of this, which has type const S *const, is assigned to an object of type S *const. Because this code was accepted, illegal assignments to members within const member functions, such as the assignment to i, were not detected.

```
struct S {
        int i;
        void f() const {
                S *const p = this;  // error
                p->i = 5;
        }
};
```

Release 2.1 correctly reports the following error for this code:

```
line 4: error: S::f() const: assignment of S::this (const struct S *const) to S *const
```

volatile Member Functions Not Implemented (§9.3.1)

Release 2.1 issues a "not implemented" error message if a volatile member function is seen. Release 2.0 silently ignored the keyword volatile when applied to a member function.

Member Functions in Local Classes Must Be Defined Inline (§9.8)

When a class is defined within a function definition (that is, a local class), all member functions of the class must be defined within the class definition itself or not at all.

For example, the following code declares the function `f2()` but fails to define it:

```
void f() {
      struct Local {
            int f1() { return 0; }
            int f2(int);
      };
      Local var;
}
```

Release 2.0 quietly accepted the above code. Release 2.1, however, issues the following warning:

```
line 6: warning:  f2() must be defined inline within local class Local
```

Protection Violations of Anonymous Union Members (§11)

Release 2.0 did not enforce access protection for members that are anonymous unions. For example, the following code was silently accepted:

```
class S {
      union { int i; double d; };
};
void f() {
      S s;
      s.i = 5; // error
};
```

Release 2.1 correctly reports an error for the assignment to `s.i` because `i` is declared in the private part of `S`.

Friend Declarations Cannot Be Class Definitions (§11.4)

The syntax for declaring a class to be a friend of another class allows the use of an *elaborated-type-specifier,* but not a complete class definition, in the declaration. Therefore, the first friend declaration in the example below is legal, but the second is not.

```
class C {
      friend struct A;                  // ok
      friend struct B { int f(); };     // error
};
```

Release 2.0 did not recognize the error in the friend declaration for `B`, but Release 2.1 issues the following error message:

```
line 3: error: friend struct B {...}
```

Access to Protected Members (§11.5)

The *Reference Manual* states that a derived class may refer to a protected member of a base class *only* if the reference is through a pointer to, reference to, or object of the derived class. For example, in the code below, although `class D` is derived from `class B`, `D::f()` cannot call the protected function `B::g()` through a `B` pointer. The same rules apply to constructors, making the calls to `B::B()` in `D::f()` illegal.

```
class B {
        B(int);
        void g(int);
protected:
        B();
        void g();
};
class D : public B { void f(); };
void D::f() {
        B b;                    // error
        B* bp = new B;          // error
        bp->g();                // error
}
```

In general, Release 2.0 reported the protection violations in code such as this. In some cases, however, no errors were reported. Such cases generally involved overloaded functions, one of which was protected, as shown in the above example.

Release 2.1 correctly generates the following messages for this code:

```
line 11: error:  D::f() cannot access B::B(): protected  member
line 12: error:  D::f() cannot access B::B(): protected  member
line 13: error:  D::f() cannot access B::g(): protected  member
```

Redundant Initializers (§12.6.1)

The following code was accepted by Release 2.0 but is incorrect because it specifies two initializers for the same object. Release 2.1 reports an error.

```
struct Point { Point(int, int); };
void f() {
      Point p(1, 2) = Point(3, 4);     // error
}
```

Illegal Function Overloading (§13)

The *Reference Manual* states that functions with parameter types that differ only with respect to `const` or `volatile` may not have the same name. Release 2.0 did not enforce this rule consistently and accepted code such as the following:

```
void f(int *);
void f(int *const); // error
```

Release 2.1, however, correctly reports an error for the second declaration of `f()`.

```
line 2: error: the overloading mechanism cannot tell a void (int *) from a void (int *const )
```

"Intersection Rule" Applied to Function Matching (§13.2)

Release 2.0 did not fully implement the "intersection rule" for function matching described in §13.2 of the *Reference Manual*. For example, the following code was accepted and a call to `f(double,double)` was generated.

```
double f(double, double);
double f(float, float);
double d = f(double(1.0),float(1.0));   // ambiguous
```

According to §13.2, however, this call is ambiguous. If you look for possible matches, parameter by parameter, you see that the set of best matches for the first parameter has only one element, `f(double,double)`, and the set of best matches for the second parameter also has only one element, `f(float,float)`. The intersection of these sets is empty, so the call is ambiguous.

For this example, Release 2.1 correctly issues the following message:

```
line 3: error: ambiguous call of f(); double (double, double) and double (float, float)
```

This change in behavior may affect class libraries that provide functions that overload system functions. For example, suppose you define a type `String` and then overload the system function `read()` to handle objects of type `String`:

```
struct String {
      String(char*);
      // ...
};
int read(int, String&, int);
```

However, you do not notice that the last parameter of the system `read()` function is an `unsigned` rather than an `int`:

```
int read(int, void*, unsigned);  // system 'read()'
```

Because Release 2.0 did not correctly implement the intersection rule, calls to the library's `read()` were considered unambiguous. Under Release 2.1 they are ambiguous because the intersection rule is strictly applied:

```
void g(int fd, char* cp) {
      (void) read(fd, cp, 3);    // ambiguous
}
```

The point here, especially for library writers, is to be careful when overloading system functions. The types of the parameters that are intended to be the same should match exactly.

Restrictions on Overloaded Operators (§13.4)

The *Reference Manual* places a number of restrictions on the ways in which operators can be overloaded. For example, `operator=()` must be a non-static member function. Release 2.1 enforces these rules more strictly than Release 2.0 did.

```
struct S {
      static operator=(int);     // error
};
```

Release 2.1 reports the following error for the above example:

```
line 2: error: S::operator=() cannot be a static member function
```

Reference Manual Changes

Release 2.1 provided a new, revised *Reference Manual*, which incorporated hundreds of customer comments on the draft *Reference Manual* distributed with Release 2.0. The Release 2.1 *Reference Manual* clarified the wording and intent of the language definition, corrected errors, and removed inconsistencies. In a very few cases, the language rules were deliberately changed, in response to feedback from programmers using C++. The revised *Reference Manual* was submitted to the American National Standards Institute (ANSI) and has been accepted as the basis for standardizing the C++ language. An annotated version of the new *Reference Manual*, entitled *The Annotated C++ Reference Manual*, was published in early 1990 by Addison-Wesley.

This section lists the changes in the Release 2.1 *Reference Manual*, ordered by section of the *Reference Manual*. To help you determine quickly which changes might impact your code, each change has been classified into one of the following categories:

- *extension*, which is implemented in Release 2.1
- *restriction*, also implemented in Release 2.1
- *clarification*, which makes a language rule more explicit and which does not affect the behavior of the C++ Language System
- *change*, for which no corresponding change has yet been made to the C++ Language System

NOTE Release 2.1 will continue to compile successfully every legal C++ program that compiled under Release 2.0. As usual, you will get a warning message if you use a construct that is no longer legal, but your program will still compile just as it did under Release 2.0. If your program compiles without any anachronism warnings, then it will work the same way when the new rules are completely phased in and the old rules are completely phased out. Remember that some anachronism warnings appear only if `+w` is specified.

New Keyword `try` (§2.4, restriction)

There is a new keyword, `try`, for exception handling. Although Release 2.1 does not implement exception handling, a warning message is issued if an identifier named `try` is encountered.

```
int try;
```

```
line 1: warning:  try is a future reserved keyword
```

NOTE

Release 3.0 recognizes the full exception handling syntax, but issues a "sorry, not implemented" message.

One Definition of an Inline Member Function (§3.3, change)

According to the Release 2.1 *Reference Manual*, an inline member function must have exactly one definition in a program. In other words, an inline member function cannot legally have different definitions in different files. Previously, this restriction was not explicitly stated.

This rule might be easily enforced in a C++ environment where a library manager keeps track of all definitions in a program, but the C++ Language System does not enforce this rule.

Character Types (§3.6.1, clarification)

The Release 2.1 *Reference Manual* states that the types `char`, `unsigned char`, and `signed char` are three distinct types. This corrects a misstatement in the previous *Reference Manual* and conforms with the ANSI C standard.

Because the C++ Language System ignores the keyword `signed`, Release 2.1 provides two character types: `char` and `unsigned char`.

Qualified Name Syntax for Nested Types (§5.1, §9.7, extension)

The Release 2.1 *Reference Manual* extends the qualified name syntax to apply to type names as well as class members. This new syntax allows a nested type to be named outside the class in which it is defined.

For example, to refer to the enumeration type `E` outside the definition of `Outer`, the syntax `Outer::E` should be used, as shown below.

```
struct Outer {
        enum E { e };// nested type
};

Outer::E var1;            // use of a nested type
```

To provide compatibility with Release 2.0, Release 2.1 also allows you to refer to a nested type name without qualification, as in the following declaration:

```
E var2;
```

Release 2.1 issues a warning message, however, for this use:

```
line 1: warning: use Outer:: to access nested enum type E (anachronism)
```

The qualified name syntax is recursive, but Release 2.1 does not implement qualified names with more than two identifiers:

```
struct S1 {
        struct S2 {
                typedef int T;
        };
};

S1::S2::T var3;             // legal, sorry in 2.1
```

For this code, the following message is issued:

```
line 7: not implemented: class names do not nest, use typedef x::y y_in_x
```

NOTE True nested types are implemented in Release 3.0, and the transition model supplied in Release 2.1 is no longer supported.

Class Arguments to `f(...)` (§5.2.2, extension)

The Release 2.0 *Reference Manual* specified that it was illegal to pass an object of a class with a constructor to a function with an ellipsis formal parameter. This restriction is lifted in the Release 2.1 *Reference Manual* and the new behavior is implemented in Release 2.1. The following code, which produced an error under Release 2.0, compiles without complaint under Release 2.1. The copy constructor is *not* invoked to pass the argument. Instead, a bit-wise copy is done.

```
struct S {
      S();
      S(const S&);
};
void f(...);

void g(S s) {
      f(s);            // legal, accepted by 2.1
}
```

Explicit Type Conversions with Empty Initializers (§5.2.3, change)

The 2.1 *Reference Manual* allows you to specify an explicit type conversion with an empty initializer, as in the following examples:

```
int i = int();

struct Empty {};
Empty e = Empty();
```

Release 2.1 does not implement this capability and reports an error instead.

```
line 1: error: value missing in conversion to int
line 4: error: cannot make a Empty
```

NOTE

Release 3.0 implements this capability.

Size of a Function (§5.3.2, restriction)

In C++, as in ANSI C, you are allowed to apply the `sizeof` operator to a pointer to a function but not to the function itself. For example, this code is legal:

```
void f();
int i = sizeof(&f);
```

but this is not:

```
int j = sizeof(f);
```

Release 2.1 enforces this restriction.

Access Protection for `operator new()` (§5.3.3, restriction)

Release 2.0 did not check access protection for calls to class-specific `operator new()`. The Release 2.1 *Reference Manual* explicitly extends access protection to calls to class-specific `operator new()`, and Release 2.1 implements this behavior. For example, the following code compiled without error under Release 2.0, but produces an error message under Release 2.1.

```
#include <stddef.h>
class C {
      void* operator new(size_t);
      void operator delete(void*);
public:
      C();
};

void f() {
      C *cp = new C;      // illegal, error in 2.1
}
```

Release 2.1 issues the following diagnostic for this code:

```
line 8: error: f() cannot access C::operator new(): private member
```

Empty Initializers for `operator new()` (§5.3.3, clarification)

The Release 2.1 *Reference Manual* explicitly allows the initialization expression in an allocation expression to be empty, as in the following examples:

```
double* dp = new double();

struct Complex {
      Complex();
      // ...
};
Complex* cp = new Complex();
```

For a built-in type, this means that an object with an undefined value is created. For a class type, this means that the default constructor is called. If there is more than one default constructor, an error is reported because the call is ambiguous. If there is no default constructor, an object with an undefined value is created.

Both Releases 2.0 and 2.1 implement this behavior correctly.

Deleting an Array (§5.3.4, extension)

It used to be necessary to specify the number of elements when deleting an array. For example, you were required to specify the expression 10 when deleting the array pointed to by p in the following code:

```
struct S { S(); ~S(); };
void f1() {
        S *p = new S[10];
        // ...
        delete [10] p;
}
```

With Release 2.1 this is no longer necessary, and the following code is now accepted:

```
void f2() {
        S *p = new S[10];
        // ...
        delete [] p; // no size necessary
}
```

Use of the old syntax is considered an anachronism, and Release 2.1 issues the following diagnostic if the +w option is specified to the CC command:

```
line 4: warning: v in 'delete[v]' is redundant; use 'delete[]' instead (anachronism)
```

This capability frees the programmer from having to keep track of array sizes. It also prevents subtle problems caused by discrepancies between the number of allocated elements and the number of deleted elements.

NOTE Release 3.0 issues an unconditional warning if this syntax is detected.

When an array is created using the placement version of operator new, destruction and deletion of that array are the user's responsibility. For example:

```
class T {
      T();
      ~T();
      // ...
};

T*
create_T_array_in_buffer(void* buff, int n)
{
      return new (buff) T[n];
}

void foo()
{
      pv = malloc(sizeof(T)*5);
      T*  pT = create_T_array_in_buffer(pv, 5);
      delete [] pT;  // does not work!!!
}
```

Here are some approaches the user can take to this problem:

```
      delete [5] pT;
```

This (anachronistic) syntax will run the destructor on the objects in the array and free the storage using the global operator `delete`. Possibly this syntax should be resurrected.

```
      T*  ppT = pT + 5;
      while (pT <= --ppT)
            ppT->T::~T();
```

This loop destroys the objects in the array but does not free the storage, appropriate in case the storage is managed by specialized code.

Type Definitions in Casts (§5.4, clarification)

The Release 2.1 *Reference Manual* clearly states that it is illegal to define a type in a cast. For example, the following declaration is illegal and is rejected by the C++ Language System:

```
enum E { e1 = (enum { z = 10 } ) 3, e2 };     // error in 2.0 and 2.1
```

Declarations in `for` Initializers (§6.5.3, §6.7, clarification)

The Release 2.0 *Reference Manual* stated that a `for` statement containing a declaration in its *for-init-statement* was not allowed to be the statement after an `if`, `else`, `switch`, `while`, `do`, or `for`. In other words, this code was illegal:

```
void f(int i) {
        if (i)
                for (int j = i; j; j--)           // error
                        ;
}
```

This restriction was an error not enforced by the Release 2.0 implementation, and the Release 2.1 *Reference Manual* omits it.

The Release 2.1 *Reference Manual*, however, does specify a related restriction: "An `auto` variable constructed under a condition is destroyed under that condition and cannot be accessed outside that condition."

Here is an example:

```
int g(int i) {
        if (i)
                for (int j = 5; j; j--)
                        ;
        return j;    // error
}
```

In the above code, `j` cannot be accessed at the point of the `return` statement because the `return` statement is outside the body of the `if` statement. According to the Release 2.1 *Reference Manual*, an error should be reported, but Release 2.1 quietly accepts this code.

NOTE

Release 3.0 correctly reports the error.

Another example:

```
struct S {
        S(int);
        ~S();
        operator int();
        S& operator--();
};
int h(int i) {
        if (i)
                for (S s = 5; s; s--)
                        ;
        return s;       // error
}
```

The destructor for `s` is invoked at the end of the `if` statement. Release 2.1 (correctly) issues the error message

```
line 11: error: s undefined
```

at the `return` statement.

Global Inline Functions Are Static (§7.1.2, §7.1.1, §3.3, change)

The Release 2.0 *Reference Manual* allowed a non-member inline function to have external linkage. The Release 2.1 *Reference Manual* specifies, however, that a name of global scope that is declared `inline` is local to its file.

Release 2.1 does not conform to these rules. For example, the following code is accepted by Releases 2.0 and 2.1: `f()` is treated as a `static` function, and a `static` definition of `f()` is laid down.

```
extern int f(int);
inline int f(int i) { return i; }       // error, not reported
int i = f(0);
int (*pf)(int) = &f;
```

Instead, the C++ Language System should report an error that `f()` cannot be redeclared as `inline` after being declared `extern`.

Use of `typedef` Name as Synonym for a Class Name (§7.1.3, clarification)

The Release 2.0 *Reference Manual* was not explicit about where a `typedef` name could be used in place of a class name. The Release 2.1 *Reference Manual* clarifies this: "The synonym may not be used after a `class`, `struct`, or `union` prefix and not in the names for constructors and destructors within the class declaration itself." These restrictions have not been implemented by Release 2.1.

```
struct S {
      S();
      ~S();
};

typedef struct S T;
S a = T();       // legal, accepted by 2.0 and 2.1
struct T *p;     // illegal, but accepted by 2.0 and 2.1

class C;
typedef class C U;
struct U {};   // illegal, but accepted by 2.0 and 2.1
```

Because typedef names cannot be used in the names of constructors, both Release 2.0 and 2.1 treat the use of a typedef name in a member function declaration as introducing an ordinary member function of that name, not a constructor. Since this is likely to be an error, the C++ Language System should, but does not, issue a warning. However, both Release 2.0 and 2.1 correctly reject the use of a typedef name in a destructor:

```
typedef struct X Y;
struct X {
      X();            // constructor
      Y(int);         // illegal, accepted by 2.0 and 2.1
      ~Y();           // illegal, detected by 2.0 and 2.1
};
```

Scope of a Nested Enumeration (§7.2, §9.7, extension)

In conjunction with the introduction of nested types, the name of an enumeration type declared within a class declaration is local to the class. This marks a change from the Release 2.0 semantics. As a result of this change, the scope of an enumerator declared within a class is the same as the scope of its enumeration type.

```
struct S {
      enum E { e1, e2 };
      // ...
};
S::E var = S::e1;   // 'E' and 'e1' have the same scope
```

const Functions (§8.2.5, restriction)

The Release 2.1 *Reference Manual* restricts the use of the const and volatile qualifiers to non-static member functions. Release 2.1 implements this restriction. Release 2.0 accepted the declarations of g() and x() below, whereas Release 2.1 correctly rejects them:

```
class C {
      int f() const;           // legal
      static int g() const;   // illegal, error in 2.1
};

void x() const;                // illegal, error in 2.1
```

Default Arguments Illegal for Overloaded Operators (§8.2.6, §13.4, restriction)

The Release 2.1 *Reference Manual* explicitly states that default arguments are illegal for user-defined operators. Release 2.1 implements this rule. The code below was accepted by Release 2.0 but is rejected by Release 2.1.

```
struct S {
      friend int operator+(S, int = 0);      // illegal, error in 2.1
      // ...
};
```

Scope of a Class Member's Initializer (§8.4, clarification)

The Release 2.1 *Reference Manual* states explicitly that an initializer for a static member is in the scope of the member's class. This rule was not explicitly given in the previous *Reference Manual*.

Release 2.1 does not apply this rule consistently. For example, in

```
const int a = 5;

struct X {
      static int a;
      static int b;
};

int X::a = 1;
int X::b = a;
```

the correct behavior is implemented: `X::b` is initialized with `X::a`.

However, default arguments for member functions are not resolved within the scope of the class. In the following code,

```
        const int y = 2;

        struct Y {
                static int y;
                static int f(int);
        };

        int Y::f(int i = y) { return i; }
```

Release 2.1 incorrectly determines that the default argument for `Y::f()` is global `y`, not `Y::y`.

NOTE

Release 3.0 correctly resolves the argument.

Reference Initializers (§8.4.3, restriction)

The Release 2.0 *Reference Manual* allowed a reference to be initialized with a temporary, as in the following declaration:

```
        int& r = 5;
```

However, the Release 2.1 *Reference Manual* has tightened the rules for reference initializations so that only `const` references may legally be initialized with non-lvalues. This means that, instead of the previous declaration, you must use the following:

```
        const int& cr = 5;
```

The Release 2.0 C++ Language System already treated temporary initializers for non-`const` reference initializations at global scope as errors, although it allowed them at local scope. To provide a smooth transition to the more restrictive rules, Release 2.1 issues an anachronism warning, under control of the `+w` option, for non-`const` reference initializations that were accepted by Release 2.0 but are now illegal.

Here are some examples:

```
int& r1 = 5;        // illegal, error in 2.0 and 2.1

struct A { A(int); ~A(); };
A& a1 = 5;                    // illegal, sorry in 2.0, error in 2.1
const A& a2 = 5;              // legal, sorry in 2.0, bad code in 2.1

int& f1();
int& r2 = f1();               // ok, 'f()' returns an lvalue

const int& r3 = 5;  // ok, 'r3' is 'const int&'

int f2(int&);
int j = f2(5);              // illegal, error in 2.0 and 2.1

void x() {
      int& r1 = 0; // illegal, 2.1 warns under +w
      A& a1 = 5;          // illegal, 2.1 warns under +w
      const A& a2 = 5;    // legal, accepted by 2.0 and 2.1
      int j = f2(5);      // illegal, 2.0 and 2.1 warn under +w
}


struct S1 {};
struct S2 {
      operator S1();
};

void f3(S1&);
void y(S2 s2) {
      f3(s2);             // illegal, 2.0 and 2.1 warn under +w
}
```

NOTE Release 3.0 issues an unconditional warning, or an error if the `+p` option is in effect.

The anachronism warnings turn into errors if the `+p` option is specified to the `CC` command.

Reuse of a Class Name by its Members (§9.2, clarification)

The Release 2.1 *Reference Manual* limits the ways in which a class name can be reused by members of the class. The rule is that a static data member, enumerator, member of an anonymous union, or nested type may not have the same name as its class.

Release 2.1 does not enforce these restrictions completely. An error is reported if an enumerator or nested type has the same name as its enclosing class, but a static data member or member of an anonymous union are not caught.

```
struct S1 {
      static int S1;                  // illegal, no error in 2.0 or 2.1
};

struct S2 {
      union { int i; float S2; };     // illegal, no error in 2.0 or 2.1
};
```

Static Data Members of Local Classes (§9.4, change)

The Release 2.1 *Reference Manual* states that static data members are not allowed for local classes. Previously, a local class could have a static data member only if no explicit initialization was required.

Release 2.1 does not enforce the new restriction properly. If a static data member of a local class is declared but never used, a warning is reported but the program links successfully.

```
int main() {
      struct S {
            static int i;
      };
      // ...
      return 0;
}
```

```
line 2: warning: static member S::i in local class S (anachronism)
```

NOTE Release 3.0 enforces this restriction, and correctly reports an error.

If the static data member is used, the program usually cannot be linked.

```
int main() {
      struct S {
            static int i;
      };
      S::i = 5;
      // ...
      return 0;
}
```

When the above code is compiled and linked, the following messages are reported on UNIX System V. They indicate that the static member `S::i` was declared but never defined:

```
CC  x.c:
line 2: warning: static member S::s in local class S
cc  -Wl,-L/c++/cfront/cycle16   x.c -lC
undefined                       first referenced
 symbol                             in file
S__main__Fv__L1::s                  /usr/tmp/CC.28949/x.o
ld fatal: Symbol referencing errors. No output written to a.out
```

No Virtual Functions in Unions (§9.5, clarification)

Because a union cannot be used as a base class, it makes no sense for member functions of unions to be declared `virtual`. The Release 2.1 *Reference Manual* states this restriction explicitly, and Release 2.1 implements it.

```
union U {
      int i;
      double d;
      virtual int f();    // error
};
```

Release 2.1 reports the following error for this code:

```
line 3: error: f(): cannot declare virtual function within union
```

Introduction of True Nested Types (§9.7, extension)

The Release 2.1 *Reference Manual* introduces true nested types. In previous versions of the C++ language, as well as in C, nested classes are treated as a lexical convenience; they are "hoisted" to the scope of the enclosing class. With Release 2.1, however, all names declared within a class definition are local to the class and are not hoisted. The new rules provide greater consistency, improved modularity, and more intuitive behavior. In addition, they remove some of the anomalies that previously occurred with nested local classes.

To avoid breaking code that worked under Release 2.0, Release 2.1 implements a transition model for nested types, which is designed to preserve the behavior of existing programs while allowing a smooth transition to the new semantics. The old Release 2.0 behavior is now considered anachronistic.

NOTE True nested types are implemented in Release 3.0, and the transition model supplied in Release 2.1 is no longer supported.

Briefly, the transition model consists of three rules:

- Programs that are legal under the old rules and mean something else under the new rules (legal or illegal) continue to follow the old rules, and a warning is issued. For example, the use of the nested type E below is illegal under the new rules, but because it was legal under Release 2.0, Release 2.1 issues a warning rather than an error.

  ```
  class X {
          enum E { };
  };
  E e;    // legal in 2.0, warning in 2.1
  ```

  Release 2.1 issues the following warning for the above declaration of e:

  ```
  warning: use X:: to access nested enum type E (anachronism)
  ```

  If the +p option (which disallows anachronistic constructs) to the CC command is specified, the anachronism warning turns into an error.

  Here is an example of code that is legal under both old and new rules, but means different things:

  ```
  extern int i;
  struct S {
          static int i;
          struct Embedded {
                  int f() { return i; }
          };
  };
  ```

  Under Release 2.0, `Embedded::f()` returned global `::i`, whereas under the new nested types rules, it should return `S::i`. In this case Release 2.1 issues a warning

```
line 6: warning: i , accessed within nested class Embedded, is visible both globally
and within enclosing class S -- using ::i (anachronism)
```

and preserves the old behavior.

The +p option has no effect on this example; the warning does *not* turn into an error.

- Programs that are legal and mean the same thing under both sets of rules behave the same.
- Programs that are legal under the new rules and illegal under the old rules follow the new rules. For example, the new qualified name syntax was illegal under Release 2.0, but is legal under Release 2.1.

```
X::E xe;        // syntax error in 2.0, legal in 2.1
```

There is one case that causes difficulty for the transition model. Consider the following program, which is illegal under the old rules because the class `Nested` is defined twice:

```
struct S {
      class Nested {};
};

void f(Nested);

struct T {
      class Nested {}; // old rules in effect; illegal in 2.0 and 2.1
};
```

This program fails under the transition model for a subtle reason. When the compiler sees the declaration of `f()`, it does not know whether `Nested` should be treated under the old or the new rules. It has to know so that it can decide how to encode the function name in the generated C code. For compatibility, it must assume the old rules. Thus when it sees the second definition of `Nested`, it reports an error.

To allow this program to compile, you must do something early on to force the program to be considered unquestionably illegal under the old rules. The easiest way to do this is to define a global class with the same name as the nested class *before* the nested class definition. In the example below, `Inner` is the nested type that is defined within two global classes and thus requires a dummy global definition:

```
struct Inner {};                // dummy class; tells the compiler
                                // to use the new nested types semantics

class C {
      class Inner { /* ... */ };// legal in 2.1, error in 2.0
};
void g(C::Inner) {}             // legal in 2.1, error in 2.0

class D {
      class Inner { /* ... */ };// legal in 2.1, error in 2.0
};
void g(D::Inner) {}             // legal in 2.1, error in 2.0
```

The above code compiles and links properly.

To preserve link compatibility with libraries compiled under Release 2.0, you should *not* force your programs to use the new rules, as is done with `Inner` in the example above. If the new rules are applied, then function names are encoded differently, and new code will not link with old libraries.

Nested Local Types (§9.7, §9.8, extension)

The transition model for nested types guarantees that code that is legal under both the old and new rules but that changes meaning under the new rules preserves its former meaning. In this situation, Release 2.1 issues an anachronism warning.

NOTE Full nested types are implemented in Release 3.0, and the transition model supplied in Release 2.1 is no longer supported.

Here is an example that involves nested local types:

```
struct Nested { int i; };
typedef int T;
enum E { e };

void f() {
        struct Local {
                struct Nested { int i, j; };
                typedef double T;
                enum E { e };
        };
        Nested n1;
        T t1;
        E e1;
}
```

In this example, `n1` had type `Local::Nested` under Release 2.0 because the declaration of `Local::Nested` was exported into the scope of `f()`. Similarly, `t1` had type `double`. Release 2.0 incorrectly reported an error for the declaration of `E` within `Local`, so `e1` was also reported as an illegal declaration.

Release 2.1 preserves this behavior (except for the bogus error) and issues the following messages:

```
line 11: warning: Nested occurs at global and nested local class scope; using class type
                  Local::Nested
line 12: warning: T occurs at global and nested local class scope; using typedef Local::T
line 13: warning: E occurs at global and nested local class scope; using enum type Local::E
```

Under the `+p` option to the `CC` command, the behavior does not change: `Local::Nested`, `Local::T`, and `Local::E` are still used. You are encouraged, however, to change your declarations to

```
Local::Nested n1;
Local::T t1;
Local::E e1;
```

to ensure that your code continues to have the same meaning after nested types are fully implemented.

Protected Derivation (§10, change)

The Release 2.0 *Reference Manual* explicitly disallowed the use of `protected` as an access specifier for a base class. The Release 2.1 *Reference Manual* lifts this restriction. However, Release 2.1 does not implement the new behavior.

```
struct B {};
struct D : protected B {};// legal, but rejected by 2.1
```

NOTE

Release 3.0 correctly implements the new behavior.

Extension of Dominance Rule to Objects and Enumerators (§10.1.1, change)

The Release 2.0 *Reference Manual* restricted the concept of dominance to apply only to functions. That is, dominance was used only when disambiguating function names in an inheritance hierarchy involving virtual base classes. With the Release 2.1 *Reference Manual*, the dominance concept is extended to data members and enumerators. However, Release 2.1 does not implement the new semantics. In the following example, Release 2.1 incorrectly considers the use of `x` to be ambiguous, even though `B::x` dominates `V::x`.

```
struct V { void f(); int x; };
struct B : public virtual V { void f(); int x; };
struct C : public virtual V {};

struct D : public B, public C { void g(); };

void D::g() {
      x++;     // legal, but rejected by 2.0 and 2.1
      f();     // legal, accepted by both 2.0 and 2.1
}
```

NOTE

The extension of dominance to objects is implemented in Release 3.0.

Inheritance of Pure Virtual Functions (§10.3, extension)

The Release 2.0 *Reference Manual* required that a derived class define or declare pure every pure virtual function in its immediate base. This restriction is lifted in the Release 2.1 *Reference Manual*; pure virtual functions are now inherited as pure virtual functions. The new behavior is implemented in Release 2.1.

For example, the following code is legal under Release 2.1, but produced an error under Release 2.0:

```
struct A {                  // abstract class
      virtual void f() = 0;
};

struct A2 : public A {};
```

Although `f()` is not redeclared as pure virtual in `A2`, Release 2.1 (but not Release 2.0) considers `A2` to be an abstract class because `A::f()` is inherited as pure virtual.

Access Specifiers in Unions (§11, change)

The Release 2.1 *Reference Manual* allows access specifiers in unions. Formerly, these were forbidden.

```
union U {
public:                     // legal
        U();
        int i;
private:                    // legal
        double d;
protected:                  // legal
        float f;
};

U u;
float f = u.f;              // protection violation
```

Release 2.1 accepts the definition of `U` shown above but does not report the protection violation.

NOTE Release 3.0 flags the protection violation.

Access to Static Members of Private Base Classes (§11.2, change)

The Release 2.1 *Reference Manual* states that a private derivation of a base class does not restrict access to the static members of the base class. Without this rule, a member function would have less access to a base class's static members than a global function.

Release 2.1 does not implement this rule consistently. For access to a static member of an immediate base class, some illegal accesses are not reported:

```
struct B {
        static void f();
};

struct D : private B {}
struct E : private D {
        void g() {
                f();            // illegal, not reported by 2.0 or 2.1
                this->f();      // illegal, not reported by 2.0 or 2.1
                B::f();         // legal, rejected by 2.0 and 2.1
        }
};
```

In the above code, the calls `f()` and `this->f()` are illegal because they refer to `f()` via the `this` pointer, and thus the access protection for `private` members is applied. The call `B::f()` is legal because it refers to `f()` directly, just as a global function could refer to `B::f()`.

NOTE Release 3.0 implements the rule consistently.

If multi-level derivation is involved, both Releases 2.0 and 2.1 are overly conservative; they report an error for `X::f()` even though it is legal.

```
struct X {
         static void f();
};
struct Y : private X {};
struct Z : public Y {
         void g() {
                  f();           // illegal, error in 2.0 and 2.1
                  this->f();     // illegal, error in 2.0 and 2.1
                  X::f();        // legal, error in 2.0 and 2.1
         }
};
```

Access Declarations (§11.3, clarification)

The Release 2.1 *Reference Manual* explicitly imposes the following restriction on access declarations: an access declaration may not adjust the access to a base class member if the derived class also defines a member of the same name.

This rule is implemented by both Releases 2.0 and 2.1:

```
struct B {
      int i;
};

struct D : private B {
      B::i;
      int i;        // error
};
```

Linkage of Friend Functions (§11.4, restriction)

The Release 2.1 *Reference Manual* specifies that the default linkage for `friend` functions is `extern`. For example,

```
static f();

struct S {
      friend f();  // ok, internal linkage
      friend g();  // 'g()' has external linkage
};

static g();        // illegal, error in 2.0 and 2.1
```

Release 2.1 warns about static friend functions such as `f()` in the example above because, although legal, these could in principle be used to subvert the protection system. Release 2.1 issues the following messages for the example above:

```
line 3: warning: static f() declared friend to class S
line 8: error: g() declared as both static and extern
```

Friendship Is Not Inherited (§11.4, clarification)

The Release 2.0 *Reference Manual* incorrectly stated that friendship is inherited. The Release 2.1 *Reference Manual* corrects this mistake. In Release 2.1, as in previous releases of the C++ Language System, friendship is *not* inherited.

Friendship Applies to Non-Functions (§11.4, clarification)

The Release 2.1 *Reference Manual* makes it explicit that class friendship extends to all members of the class — not just to functions. Release 2.0 and Release 2.1 both implement this behavior. For example,

```
class X {
      enum { e = 100 };
      friend class Y;
};

class Y {
      int arr[X::e];      // legal, accepted by 2.0 and 2.1
};
class Z {
      int arr[X::e];      // error, 'X::e' is private
};
```

Scope of Friend Functions (§11.4, §9.7, change)

The Release 2.1 *Reference Manual* states that a `friend` function defined within a class declaration is in the lexical scope of that class, just like a member function.

In general, Release 2.1 does not implement this rule. Consider the following example:

```
extern int s;
extern int e;

struct S {
      static int s;
      enum { e = 5 };
      friend f() { return e; }  // which 'e'?
      friend void g(int = s) { };          // which 's'?
};
```

According to the Release 2.1 *Reference Manual*, `f()` returns `S::e` and the default argument for `g()` is `S::s`. Instead, both Release 2.0 and 2.1 incorrectly resolve these names to `::e` and `::s` respectively.

NOTE Release 3.0 resolves these names correctly.

If the declaration of a `friend` function within a class declaration uses a nested type, however, the nested type name is resolved according to the new semantics.

```
typedef void* T;
struct X {
      typedef int T;
      friend T h(T t);
};
```

In the above example, Release 2.1 treats `h()` as having type `int(int)`, not `void*(void*)`.

Default Constructors (§12.1, change)

The Release 2.0 *Reference Manual* explicitly stated that a default constructor is a constructor with no formal parameters, thereby excluding constructors that can be called with no arguments by virtue of having default arguments. The Release 2.1 *Reference Manual* lifts this restriction; the constructor in the example below is now considered a default constructor.

```
struct S {
      S(int = 0);
};
```

Release 2.1 does not conform to this rule. Instead, it adheres to the old definition of default constructor.

Here are some examples:

```
S s1[2];            // legal, sorry in 2.0, error in 2.1
S s2[2] = { 1 };    // legal, sorry in 2.0, sorry in 2.1

struct X {
      S s[2];             // legal, sorry in 2.0, error in 2.1
};

void f() {
      S* p = new S[2];    // legal, error in 2.0 and 2.1
}
```

NOTE

Release 3.0 correctly conforms to this rule.

Constructor and Destructor Declarations (§12.1, §12.4, §9.3.1, clarification)

The Release 2.1 *Reference Manual* specifies that constructors and destructors cannot be declared `const`, `volatile`, or `static`. Release 2.1 correctly reports an error for constructors and destructors that are declared `static`, but it incorrectly allows constructors and destructors to be declared `const`. Release 2.1 does not implement `volatile` member functions at all; these are rejected with a "not implemented" message.

```
struct S {
      static S();             // illegal, error in 2.0 and 2.1
      static ~S();            // illegal, error in 2.0 and 2.1
};

struct T {
      T() const;              // illegal, but accepted by 2.1
      ~T() const;             // illegal, but accepted by 2.1
      T(char*) volatile;      // illegal, sorry in 2.1
};
```

NOTE

Release 3.0 correctly reports these errors.

Destructors for Built-In Types (§12.4, change)

The Release 2.1 *Reference Manual* allows explicit destructor calls for any built-in type, as in the example below. However, Release 2.1 does not implement this syntax.

```
void f(int* p) {
      p->int::~int();         // legal, but error in 2.1
};
```

NOTE Release 3.0 correctly implements this syntax.

Delete Operator (§12.5, change)

The Release 2.1 *Reference Manual* tightens the rules for the `delete` operator. Only one `operator delete()` may be declared per class, and the global `operator delete()` may not be overloaded. Release 2.1 does not enforce these restrictions.

For example, the second declaration of the `delete` operator in each scope below is illegal, but the code is accepted by both Release 2.0 and 2.1.

```
typedef unsigned int size_t;

void operator delete(void*);
void operator delete(const void*);           // error, not reported

struct S {
      void* operator new(size_t);
      void* operator new(size_t, void*);
      void operator delete(void*);
      void operator delete(void*, size_t);   // error, not reported
};
```

NOTE Release 3.0 correctly reports these errors.

Generating the Default Assignment Operator (§12.8, clarification)

The Release 2.1 *Reference Manual* states the condition under which a default assignment operator is generated differently from the old *Reference Manual*. Formerly, the condition was the following:

> "If a class `X` has any `X::operator=()` defined, even one that takes an argument of a type unrelated to `X`, `X::operator=(const X&)` will not be generated."

The Release 2.1 *Reference Manual* says

> "If a class `X` has any `X::operator=()` that takes an argument of class X, the default assignment will not be generated."

The new description reflects the behavior of Release 2.0 and 2.1.

Argument Matching Rules (§13.2, clarification)

Several details about the function matching rules have changed.

- In the Release 2.0 *Reference Manual* there was a rule that a call needing only standard conversions is preferred over one requiring user-defined conversions. This rule has been eliminated in the Release 2.1 *Reference Manual* and the new semantics have been implemented in Release 2.1. For example,

  ```
  struct Complex { Complex(double); };
  void f2(int, Complex);
  void f2(double, double);

  void y2() {
          f2(3, 4);     // ambiguous
  }
  ```

  For this code, Release 2.1 correctly reports an ambiguity.

- The second function matching change involves the treatment of arguments of type `T` that require temporaries. The Release 2.0 *Reference Manual* specified that a match with conversions requiring temporaries was a legal match. So, for example, the call to `f3(char&)` in the following code was legal and was accepted by Release 2.0:

  ```
  void f3(char&);
  void x3() {
          f3('c');
  }
  ```

  Furthermore, since standard conversions were preferred to conversions requiring temporaries, the *Reference Manual* specified that the call to `f4()` below would be resolved to `f4(int)`. Instead, Release 2.0 resolved it to `f4(char&)`:

```
void f4(int);
void f4(char&);
void x4() {
      f4('c');
}
```

Under the new rules, the calls to `f3()` and `f4()` are in error because a non-`const` reference cannot be initialized with a non-lvalue (see §8.4.3). However, Release 2.1 does not report these errors and instead preserves the Release 2.0 behavior by resolving the calls to `f3(char&)` and `f4(char&)` respectively.

NOTE

Release 3.0 correctly reports errors in this situation.

Prefix and Postfix Increment and Decrement Operators (§13.4.7, change)

The Release 2.0 *Reference Manual* provided no way to distinguish user-defined prefix increment and decrement operators from postfix increment and decrement operators. The Release 2.1 *Reference Manual* specifies a separate syntax for defining prefix and postfix increment and decrement operators. The prefix increment and decrement operators take one argument (the implicit `this` argument for a member function), whereas the postfix version takes two arguments (including the implicit `this` argument). For example,

```
struct S {
      operator++();        // 2.0: prefix or postfix
                                 // 2.1: prefix, but not implemented as such
      operator++(int);           // 2.1: postfix ++, not implemented
};
```

However, Release 2.1 does not recognize the new syntax. Use of the postfix form results in the following error message:

```
line 4: error:  S:: operator ++() takes no argument
```

NOTE

Release 3.0 correctly recognizes this syntax.

ANSI C Preprocessing (§16, change)

The description of preprocessing in the Release 2.1 *Reference Manual* reflects the rules of ANSI C rather than of K&R C. Because the C++ Language System does *not* include a preprocessor, the actual preprocessing behavior of Release 2.1 depends on the preprocessor resident on the host machine.

New Warning Messages

"Not Used" Warning Messages Reported More Consistently

Release 2.1 issues warning messages more consistently if an object is declared but not used.

For example, Release 2.0 did not issue a "not used" message for the following code:

```
int f() {
        int array[5];
        return 0;
}
```

Release 2.1 issues a warning that `array` is not used.

Warning for Pure Virtual Destructors (§10.3, §12.4)

Release 2.1 issues a new warning if a pure virtual destructor is declared but not defined. For example, the code

```
struct B {
        // ...
        virtual ~B() = 0;
};
```

elicits the warning

```
line 1: warning: please provide an out-of-line definition: B::~B() {}; which is needed
by derived classes
```

to remind you that a definition of `B::~B()` is required.

To understand why a pure virtual destructor of an abstract class must be defined, consider what happens when a class `D` is derived from the class `B` defined above:

```
struct D : B {
        // ...
        virtual ~D();
};
D::~D() { /* ... */ }
```

The *Reference Manual* says that base class destructors are implicitly executed after the destructors for their derived classes (§12.4). This means that the compiler will generate code to call `B::~B()` at the end of `D::~D()`. Therefore `B::~B()` must have a definition; otherwise, a link-time error will occur because the definition is missing.

Why doesn't the compiler implicitly generate an empty definition for `B::~B()`? The reason is that it is legal for the user to define a `B::~B()` that is not empty! If the compiler generated an empty `B::~B()` in one compilation and the user defined a non-empty `B::~B()` in another compilation, then there would be two different definitions of the destructor. Although this inconsistency would probably be detectable at link time, it is preferable to avoid the inconsistency altogether by requiring the user to define the destructor explicitly.

Anachronism Warning Messages

Release 2.1 issues warning messages for all uses of anachronisms. The section "Future Compatibility Issues" in this chapter describes these messages in more detail.

Library Changes

`iostream::get()` and `iostream::put()` Now Inline

The Release 2.0 version of the `iostream` library declared `iostream::get()` and `iostream::put()` to be `inline`, but both functions were too complex to be successfully inlined. The Release 2.1 implementations of these functions have been changed so that most calls can be generated inline. For example, the call to `is.get()` is inlined by Release 2.1:

```
#include <iostream.h>
void f() {
      istream is(0);
      char c;
      is.get(c);
}
```

Task Library Ported to Amdahl UTS Computers

For Release 2.1 the task library has been ported to a new platform, Amdahl UTS. To build the task library for the Amdahl UTS computer, either set `MACH=uts` in the top level `makefile` or specify it on the command line when building the task library. For example,

```
make MACH=uts libtask.a
```

`patch`

The file `BSDpatch.c` has been modified so that `patch` works under BSD Release 4.3 running on DEC VAX computers.

Future Compatibility Issues

Anachronisms

The C++ Language System provides several extensions to the C++ language to enable users to make a gradual transition from previous versions of the C++ language to the current definition, which is specified in the *Reference Manual*. In general, these extensions allow constructs to be used that are no longer legal under the current definition, but were previously legal. The +p option disables most of these extensions so that only the "pure" language is accepted.

The following set of extensions were provided in Release 2.0 and 2.1, and most have been phased out in Release 3.0. Most of these extensions are listed and explained in §B.3 of the *Reference Manual*. The complete list appears below, with additional references to sections of the *Reference Manual* and example programs that demonstrate each anachronism.

Release 2.1 reports uses of these extensions, except the last two, by issuing a warning message, as shown. Each of these messages has the string `(anachronism)` at the end. All of the anachronism warnings are issued unconditionally, except as noted.

In most cases, anachronisms that were warned about by default in Release 2.1 are considered errors by Release 3.0. Anachronisms that produced warnings only when the +w option in effect in Release 2.1 are now warnings by default and will be disallowed in the next release.

- use of the `overload` keyword (§2.4)

  ```
  overload f;
  ```

  Release 2.1 – warning under the +w option

  ```
  line 1: warning: 'overload' used (anachronism)
  ```

  Release 3.0 – unconditional warning, or error if the +p option is in effect

- use of `.` instead of `::` for scoping (§5.1)

  ```
  struct S {
          int f();
  };
  int S.f() { return 0; }
  ```

  Release 2.1 – warning

```
line 4: warning: '.' used for qualification; please use '::' (anachronism)
```

Release 3.0 – error

- use of the `delete [n]` syntax (§5.3.4)

```
struct S { S(); ~S(); };
void f() {
      S* p = new S[10];
      // ...
      delete [10] p;
}
```

Release 2.1 – warning under the +w option

```
line 5: warning: v in 'delete[v]' is redundant; use 'delete[]' instead (anachronism)
```

Release 3.0 – warning under the +p option

- cast of a bound pointer (§5.4, §B.3.4)

```
struct S {
      int f();
} s;
typedef int (*PF)();
PF pf = (PF) &s.f;
```

Release 2.1 – warning

```
line 5: warning: address of bound function (try using ''S ::*'' for
                 pointer type and ''&S ::f'' for address) (anachronism)
```

Release 3.0 – error

- assignment of a value of integral type to an enumeration type (§7.2)

```
enum E { e1, e2 };
void f(int i) {
        E local = i;
}
```

Release 2.1 – warning

```
line 3: warning:  int  assigned to  enum E (anachronism)
```

Release 3.0 – error

- non-const reference initializer not an lvalue (§8.4.3)

```
void f() {
        int& r = 5;
}
```

Release 2.1 – warning under the +w option

```
line 2: warning: initializer for non-const reference not an lvalue (anachronism)
```

Release 3.0 – unconditional warning, or error if the +p option is in effect

- non-const member function called for a const object (§9.3.1)

```
struct S {
        int f();
};
extern const S s;
int i = s.f();
```

Release 2.1 – warning

```
line 4: warning: non-const member function S::f() called for const object (anachronism)
```

Release 3.0 – error

- static data member declared within a local class (§9.4)

```
int main() {
        struct S {
                static int i;
        };
        // ...
        return 0;
}
```

Release 2.1 – warning

```
line 3: warning: static member S::i in local class S (anachronism)
```

Release 3.0 – error

- use of an unqualified nested type name outside its enclosing class definition (§9.7)

```
struct Enclosing {
        enum Nested { e1, e2 };
};

Nested var;
```

Release 2.1 – warning

```
line 5: warning: use Enclosing:: to access nested enum type Nested (anachronism)
```

Release 3.0 – error

- use of an identifier that is declared at global and local scope within a nested type definition (§9.7)

```
int i;
struct S {
        static int i;
        struct Nested {
                static int f() { return i; }
        };
};
```

Release 2.1 – warning

```
line 5: warning: i, accessed within nested class Nested, is visible both globally
and within enclosing class S -- using ::i (anachronism)
```

Release 3.0 – accepted under complete nested semantics

- use of a type name that is declared at global scope and within a local nested class (§9.7)

```
typedef int T;

void f() {
        struct Nested {
                typedef char T;
        };
        T var;
}
```

Release 2.1 – warning

```
line 7: warning: T occurs at outer and nested local class scope;
using typedef Nested::T (anachronism)
```

Release 3.0 – accepted under complete nested semantics

- first parameter of `operator new()` not of type `size_t` (§12.5)
- second parameter of `operator delete()` not of type `size_t` (§12.5)

```
struct S {
           void* operator new(long);
           void operator delete(void*, long);
};
```

Release 2.1 – warning

```
line 2: warning: operator new() first argument should be size_t (anachronism)
line 3: warning: operator delete()'s 2nd argument should be a size_t (anachronism)
```

Release 3.0 – error

- `operator=()` declared as a global function (§13.4.3)

```
struct S { /* ... */ };
S& operator=(S&, S&);
```

Release 2.1 – warning

```
line 2: warning: non-member operator =() (anachronism)
```

Release 3.0 – error

- use of the "Classic C" style function definition syntax (§B.3.1)

```
int f(i)
int i;
{
        return i;
}
```

Release 2.1 – warning

```
line 1: warning: old style definition of f() (anachronism)
```

Release 3.0 – remains a warning to maintain "Classic C" compatibility

- use of an old-style base class initializer in a constructor definition (§B.3.2)

```
class B {
        int b;
public:
        B(int i) { b = i; }
};
struct D : public B {
        D(int i) : (i) {}
};
```

Release 2.1 – warning

```
line 7: warning: name of base class B missing from base class initializer (anachronism)
```

Release 3.0 – remains a warning to allow portability between Release 2.0 and Release 3.0.

- assignment to `this` (§B.3.3)

```
extern void* myalloc(unsigned int);
struct X { X(); };
X::X() {
      if (this == 0) {
            this = (X*) myalloc(sizeof(X));
            // ...
      }
      else {
            this = this;
            // ...
      }
}
```

Release 2.1 – warning under the +w option

```
line 3: warning: assignment to this (anachronism)
```

Release 3.0 – unconditional warning, or error if the +p option is in effect

- use of the c_plusplus preprocessor macro (§16.1)
- static data member declared but never defined (§9.4)

NOTE This anachronism is enforced for template classes, and will be disallowed in the next release.

The last two extensions — use of the c_plusplus preprocessor macro and implicit definition of a static data member — are difficult for the compiler by itself to detect, and do not produce warning messages. Uses of c_plusplus are generally known only to the preprocessor, and implicit definitions of static data members can only be detected at link time, or after linking has taken place. You can look for uses of c_plusplus by scanning your source code for that pattern. On some systems you can also find implicit definitions of static data members by examining the executable file produced by the linker for instances of uninitialized data with class-scope names.

The Old Stream Library

The old `stream` library, which is available as `lib Ostream.a` in Release 2.1, is not provided with this release of the C++ Language System.

A Appendix A

Known Problems

The following sections describe specific problem areas that remain in the C++ Language System. Where appropriate, the related sections of the *Reference Manual* are noted.

Multiple Definitions (§3.3)

- In K&R C and in the ANSI C standard, implementations are free to decide how to treat multiple, uninitialized definitions of objects with external linkage at global scope.

  In C++ exactly one definition, initialized or uninitialized, may occur in a single program. In order to enforce this rule, the C++ Language System initializes most global variables to `0`. However, in order to reduce object file space, no initialization is done for global arrays. Similarly, since most K&R C compilers reject such code, no initialization is done for unions or for classes or arrays of classes whose first element is a union.

  Users should be aware that invalid multiple definitions for these cases may go undetected.

- For compatibility with previous releases of the C++ Language System, static data members of non-template classes are implicitly defined. This means that multiple definitions of the same static member in multiple files will result in multiple calls to the constructor.

  For example, suppose that the header file `a.h` defines a class with a static member:

  ```
  struct A { A(); };
  struct B { static A ab; };
  ```

  and file `a.c` contains the definition of the static data member:

  ```
  #include "a.h"
  A B::ab;
  ```

  as does file `main.c`:

  ```
  #include "a.h"
  A B::ab;
  main() { /* ... */ }
  ```

  When these files are compiled and linked together, the duplicate definitions of `B::ab` will not be reported and the constructor for `B::ab` will be called twice.

Global Inline Functions Are Static (§7.1.2, §7.1.1, §3.3)

The Release 2.0 *Reference Manual* allowed a non-member inline function to have external linkage. The Release 3.0 *Reference Manual* specifies, however, that a name of global scope that is declared `inline` is local to its file.

Release 2.1 and Release 3.0 do not conform to these rules. For example, the following code is accepted by Releases 2.0, 2.1 and 3.0: `f()` is treated as a `static` function, and a `static` definition of `f()` is laid down.

```
extern int f(int);
inline int f(int i) { return i; }       // error, not reported
int i = f(0);
int (*pf)(int) = &f;
```

Instead, the C++ Language System should report an error that `f()` cannot be redeclared as `inline` after being declared `extern`.

Reuse of a Class Name by its Members (§9.2)

The Release 3.0 *Reference Manual* limits the ways in which a class name can be reused by members of the class. The rule is that a static data member, enumerator, member of an anonymous union, or nested type may not have the same name as its class.

Release 3.0 does not enforce these restrictions completely. An error is reported if an enumerator or nested type has the same name as its enclosing class, but a static data member or member of an anonymous union are not caught.

```
struct S1 {
      static int S1;                   // illegal, no error
};

struct S2 {
      union { int i; float S2; };      // illegal, no error
};
```

Unions (§9.5)

- The C++ Language System invalidly allows union members of a type which contains a user defined assignment operator. It correctly detects union members of a type with a constructor or destructor:

```
struct assign {
        //...
        assign& operator =(const assign&);
};

struct ctor {
        //...
        ctor();
};

struct dtor {
        //...
        ~dtor();
};

union U {
        assign a;               // undetected error
        ctor b;                 // correctly detected
        dtor c;                 // correctly detected
};
```

The following correct errors are reported

```
line 16: error:  member U::b of class ctor with constructor in union
line 16: error:  member U::c of class dtor with destructor in union
```

but there should be a similar error

```
line 16: error:  member U::a of class assign with operator= in union
```

Nested Types (§9.5)

This release completes the introduction of true nested types. There are two known problems in the new implementation:

- The C++ Language System generates invalid C code for uses of nested classes as virtual base classes:

```
struct Outer {
        struct InnerBase {
                                //...
        };
        struct InnerDerived : public virtual Outer::InnerBase {
                                //...
        };
};
```

- Protection has not yet been implemented for nested types:

```
class A {
        enum E {/*...*/};  // private
        //...
};

A::E evar;                      // undetected error,
                                // A::E should not be accessible
```

Pure Virtual Functions (§10.3)

- The C++ Language System fails to detect the use of a pure virtual function inside the class's own destructor. Other invalid uses of a pure virtual function are correctly detected:

```
struct Base {
        Base();
        ~Base();
        virtual void f() =0;
};

Base::~Base() {
        f();                    // undetected error
};

Base::Base() {
        f();                    // correctly detected
};

Base f();// correctly detected
f(Base);                        // correctly detected
```

The following errors are correctly reported

```
line 13: error: call of pure virtual function Base::f() in constructor Base::Base()
line 15: error: abstract class Base cannot be used as a function return type
line 15:     Base::f() is a pure virtual function of class Base
line 16: error: abstract class Base cannot be used as an argument type
line 16:     Base::f() is a pure virtual function of class Base
```

but there should be a similar error reported for the case involving the destructor.

Friendship (§11.4)

- The C++ Language System invalidly extends friendship throughout the class hierarchy in a multiple inheritance lattice:

```
class base1 {
        friend void foo();
protected:
        int i;
};

class base2 {
protected:
        int j;
};

class derived : public base1, public base2 {
protected:
        int k;
public:
        derived();
};

void foo() {
        derived der;
        der.i = 1;              // ok, foo is friend of base1
        der.j = 2;              // undetected error
        der.k = 3;              // detected error
};
```

The following correct error is reported:

```
line 23: error:  foo() cannot access derived::k: protected  member
```

but there should be a similar error for the assignment to der.j:

```
line 22: error:  foo() cannot access derived::j: protected  member
```

Static Members (§11.5)

- Release 3.0 is too restrictive in its treatment of protected static members of a base class when they are accessed by friends of a derived class. The following example should compile without complaint:

  ```
  class S1 {
  protected:
          static int s;
  };

  struct S2 : public S1 {
          friend int f1() { return S1::s; }    // legal
          friend int f2() { return S2::s; }    // legal
  };
  ```

  Instead, the following errors are incorrectly reported:

  ```
  error:  f2() cannot access S1::s: protected  member
  error:  f1() cannot access S1::s: protected  member
  ```

  This problem can be circumvented by referring to the base class's static member through an object of the derived class:

  ```
  friend int f3(const S2& s2) { return s2.s; }
  ```

- Section 11.5 of the reference manual states that "a friend or a member function of a derived class can access a protected static member of a base class" and section 12.5 specifies that "An X::operator new() [delete()] for a class X is a static member". The C++ Language System fails to allow the implied access to static members new and delete:

```
typedef unsigned int size_t;

class base {
protected:
        void * operator new(size_t);
        void operator delete(void *);
        void static_memf();
};

class derived : public base {
public:
        void f() {
        base *b = new base();   // invalidly rejected
        delete b;               // invalidly rejected
        static_memf();          // correctly allowed
        };
};
```

Produces the following invalid errors:

```
line 10: error:  derived::f() cannot access base::operator delete(): protected  member
line 10: error:  derived::f() cannot access base::operator new(): protected  member
```

Access control and constructors and destructors (§12.3)

- The reference manual stipulates that normal access control is applied to constructors and destructors. This implies that making a destructor private or protected disallows automatic and static allocation of such objects since they could never be destroyed. The C++ Language System correctly enforces this rule in most situations. However, it invalidly creates temporaries of such types when passing arguments as const references and then invalidly calls the private destructor:

```
class A;

struct B {
        B();
        ~B();
        void foo (A const&);
};

class A {
private:
        ~A();
        void operator=(A&);
        A(A&);
public:
        A(B);
};

main() {
        B b;

        A a(b);                 // correctly detected
        A a1 = A(b);            // correctly detected

        b.foo(b);               // undetected error
        b.foo(A(b));            // undetected error
};
```

The following correct errors are reported:

```
line 21: error:  main() cannot access A::~A(): private  member
line 22: error:  main() cannot access A::~A(): private  member
```

but there should be similar errors for the calls to b.foo.

- The C++ Language System also fails to detect invalid calls to operator delete for classes with a private destructor:

```
class B {
        ~B();                   // private
};

main() {
        B b;                    // correctly detected

        B* bp = new B;          // legal

        delete bp;              // undetected error
};
```

Protection and Destructors (§12.4)

- If a base class has a private destructor, only member and friend functions of that class may destroy objects of that class. However, Release 3.0 fails to enforce this protection for derived classes that do not redefine the destructor at the same protection level. Thus, protection can be overridden by a derived class that simply fails to declare a destructor or by a derived class that declares a destructor with less restrictive protection.

  For example, the following code compiles without complaint:

  ```
  class B {
  private:
          ~B();
  };

  class D: public B {};

  class D2: public B {
  public:
          ~D2() { }
  };

  void f() {
          D d;                    // undetected error
          D2 d2;                  // undetected error
  }
  ```

  Instead, `f()` should not be able to create objects of type `D` or `D2`.

Template Classes (§14.2)

- In processing templates, the C++ Language System builds up internal representations of template classes and functions but does not type check or otherwise validate user code until a template is instantiated. For example, in the code below, the definition of the non-existent static member y is not detected until an object of the template type A is declared:

  ```
  template <class T> struct A {
          static int x;
  };

  template <class T> int A<T>::y = 37;    // error not detected until
                                         // an object of type A<...>
                                         // is declared
  ```

  It is a good idea, therefore, when developing code that defines template classes or functions to include simple references to the template type to force instantiation time type checking and other semantic checking. For example, if the above code had been compiled with a use of template A, the error would have been correctly reported:

  ```
  template <class T> struct A {
          static int x;
  };

  template <class T> int A<T>::y = 37;

  A<int> _dummy;
  ```

  Produces the following correct error messages:

  ```
  line 8: error:  y: only static data members can be parameterized
  ```

Template Declarations(§14.5)

- If two class templates refer to each other, one referring to the other only via a pointer or reference, and the other referring to the first in a way that requires the full definition to be known, the C++ compiler may produce errors depending on the order in which uses of the templates appear in user code. For example:

```
template <class T> class B;

template <class T> class A {
        B<T>* ptr;
};


template <class T> class B {
        A<T> not_a_ptr;
};

A<int> something; //Causes error
```

produces the following invalid errors:

```
line 9: error:  A undefined, size not known
line 9:      error detected during the instantiation of B <int >
line 9:     the instantiation path was:
line 3:       template: B <int >
line 12:     template: A <int >
```

If a use of `A<int>` is seen before a use of `B<int>`, the instantiation will either fail, or produce invalid C code. If a reference to `B<int>` is seen first, there are no errors.

The workaround is to add a dummy reference to `B<int>` before the first reference to `A<int>`:

```
typedef B<int> dummy;
A<int> something;
```

Member Function Templates (§14.6)

- In processing templates, the C++ Language System builds up an internal representation for the template, but does not actually process instantiations until the end of the file. This is to allow for correct processing of template specializations. However, this approach has several side effects with respect to processing inline member function templates. To be inlined, member functions must be defined inside the class definition. For example, the Vector constructor in the following code will be laid down out of line in each file rather than being inlined:

```
template<class T> class Vector {
public:
         inline Vector(int size);
         T& operator[](int i) {return vec[i];}
private:
         int size;
         T* vec;
};

template<class T>
inline Vector<T>::Vector(int sz) : vec(new T[size=sz]) {}

main()
{
         typedef char *String;

         String a = "foo_bar";
         Vector<String> str_vec(2);
         str_vec[0] = a;
}
```

Similarly, errors will be reported if a member function is not declared to be inline in the class template but is subsequently defined as inline. For example:

```
template <class T> class A {
public:
         void f(T t);
};

template <class T> inline void A<T>::f(T t)
{
}

main()
{
         A<int> a;

         a.f(0);
}
```

produces the following errors:

```
line 7: error: A <int>::f() declared with external linkage and called before defined as inline
line 7:         error detected during the instantiation of A <int >
line 24:        is the site of the instantiation
```

Preprocessing (§16)

- The C++ Language System does not include a version of cpp, but instead uses the cpp resident on the host machine. Many cpps do not recognize C++ comments. This can sometimes lead to surprising results.

  For example, if your preprocessor has not been modified for C++, C++-style comments (//) in a macro definition will not be ignored:

  ```
  #include <stream.h>
  #define A 5 // define something

  main() {
          cout << A;
  }
  ```

  The comment in the macro definition results in the following error message:

  ```
  line 6: error: ';' missing after statement
  ```

  Similarly, use of a macro name within a // comment

  ```
  #include <generic.h>

  main() {
           int a;     // declare variables
           float f;
  }
  ```

  sends many preprocessors into an infinite loop expanding the macro `declare`, which is defined in `generic.h`. Note that `generic.h` may be included by other files as well. For example, `stream.h` indirectly includes `generic.h`.

  Finally, interactions between C comments and C++ comments should be noted. For example,

```
//** this looks like a C-style block comment to cpp
#include <stddef.h>
/* this is a C-style block comment */
main()
{
        char *c = NULL;
}
```

results in the following error message if cpp does not properly handle C++-style comments:

```
line 1: error:  synrax error
line 4: error:  NULL undefined
```

Incompatibilities with the ANSI C Standard

- Release 3.0 fails to accept ANSI C-conforming declarations for functions taking function arguments. For example,

  ```
  void f(int());
  ```

  produces the following error:

  ```
  line 1: error:  bad base type: void f
  ```

  If a function pointer is specified as a parameter, like this,

  ```
  void f(int(*)());
  ```

  the code is accepted.

Missing or Extraneous Warnings

- The C++ Language System is sometimes too cautious in deciding when it is necessary to generate code to invoke a destructor. As a result, unreachable code containing destructor invocations is sometimes generated, and some C compilers warn about this unreachable code. For example:

```
struct A {
      A();
      ~A();
};
void f(int i) {
      switch(i) {
      case 0: {
            A a;
            break;
            };
      }
}
```

This code may result in the C compiler warning

```
line 6: warning: statement not reached
```

which can be safely ignored.

- Similarly, for the following case, destructors are properly called on each return path, but also at the end of the function:

```
struct A {
      A();
      ~A();
};

int f(int i) {
      A a;
      if (i)
            return i;
      else
            return i;
}
```

- C++ allows conversions that may involve loss of information. Because such conversions are likely to introduce errors in the user's code, the C++ Language System should warn about shortening conversions. In general, such conversions are diagnosed only when assigning a `float`, `double`, or `long` value to one of the smaller integral types. The following shortening conversions are accepted without complaint:

```
extern char c;
extern short s;
extern unsigned char uc;
extern unsigned short us;
extern int i;
extern long l;
extern float f;
extern double d;

void x() {
         f = d;
         c = i;
         l = d;
         l = f;
         c = s;
         s = i;
         uc = i;
         us = i;
}
```

- Some instances of "used before set" warnings are invalid. For example, the code below causes the C++ Language System to warn incorrectly that s is used before set.

```
struct S {
         short a;
         short b;
};
void f() {
         S s;
         s.a = s.b = 0;          // invalid ''used before set'' warning
}
```

Use of the sizeof operator also leads to invalid "used but not set" warnings, as in the following code:

```
void g() {
       char *p;
       int i = sizeof(p);  //invalid ''used but not set'' warning
}
```

Other Problems with Compiling and Linking

- Single files compiled directly to an a.out which contain specializations of templates will occasionally fail. For example:

  ```
  extern "C" void printf(...);
  template <class T> int foo(T) { return 1; }

  main()
  {
          int  i = 3;
          printf("%d\n", foo(i));  // should print 0
  }

  int foo(int) { return 0; }
  ```

  Invalidly produces the following error from the c compiler:

  ```
  line 11: redeclaration of foo__Fi
  ```

  This is because the single file case is optimized to avoid automated instantiation support and the system invalidly instantiates the template version of foo(int). When the subsequent specialization is seen, the template instance has already been created. This problem can be avoided either by ensuring that all specializations preceed any use:

  ```
  extern "C" void printf(...);
  template <class T> int foo(T) { return 1; }

  int foo(int) { return 0; }

  main()
  {
          int  i = 3;
          printf("%d\n", foo(i));  // should print 0
  }
  ```

  or by compiling CC -ptn which ensures that full automated instantiation support is invoked.

- At present, function templates declared in header files have only the raw name extracted and added to the name mapping files. So for:

  ```
  template <class T, class U> void f(T, int, U);
  ```

  `f` will be extracted. This works for many simple cases, but fails in some cases where two different headers declare a function template with the same or different formal arguments.

- For compatibility with previous releases, the argument type of __vec_new and vec_delete under the +a1 ANSI option are incorrect. Strict ANSI compliance would declare these functions as:

  ```
  __vec_new(void*, int, int, void(*)());
  __vec_delete(void *, int, int, void(*)(), int, int);
  ```

  However, doing so would lead to bootstrapping problems when building the compiler using libC compiled with earlier releases.

- For compatibility with previous releases, static class members and static template class members created from a template specialization are not initialized to 0. This may lead to problems with linkers that do not pull in object files from an archive if there are no initialized external references. If a file exists whose only external dependency is an uninitialized static data member or an uninitialized global array, these linkers will fail to include the object file and a runtime error will occur.

  For example, suppose ab.h defines a class with a static data member:

  ```
  // file "ab.h"
  struct A {
        int i;
        A() { i = 3; }
  };

  struct B {
        static A a;
  };
  ```

  and file ab.c defines the static member

  ```
  // file "ab.c"
  #include "ab.h"
  A B::a;
  ```

  and file main.c refers to the static member

  ```
  // file "main.c"
  #include <stdio.h>
  #include "ab.h"

  main() {
        printf ("%d\n", B::a.i);
        // ...
        return 0;
  }
  ```

  If these files are directly compiled and linked, the expected output of 3 is printed on the standard output. However, if the file ab.c is compiled and stored in a library and later linked with main.c, then the program prints 0 if a linker that does not resolve uninitialized data is used.

- When two files are compiled separately in separate directories, but contain identically named objects of the same class, problems will occur when an attempt is made to link the two object files.

  For example, suppose you have a header file `x.h` in your current directory, and you have two subdirectories `a` and `b`, each of which contains a file named `x.c`.

  ```
  // file "x.h"
  struct X {
        virtual void f() {};
  };

  // file "a/x.c"
  #include "../x.h"

  void f() {
        X x;
  }

  // file "b/x.c"
  #include "../x.h"

  main() {
        X x;
        // ...
        return 0;
  }
  ```

  If these files are compiled separately and an attempt is made to link them together,

  ```
  cd a
  CC -c x.c
  cd ../b
  CC -c x.c
  cd ..
  CC a/x.o b/x.o
  ```

  they will fail to link, and messages similar to the following will be generated by the linker:

  ```
  ld: Symbol ___vtbl__1X__x_c in b/x.o is multiply defined. First defined in a/x.o
  ld: Symbol ___ptbl__1X__x_c in b/x.o is multiply defined. First defined in a/x.o
  ld fatal: Error(s). No output written to a.out
  ```

These errors occur because the names of the virtual tables and associated housekeeping information for the X objects in files a/x.c and b/x.c are encoded identically, so the symbols are multiply defined.

A workaround for this problem is to rename one of the files or to use a longer pathname when compiling these files.

Library Problems

- The implementation of the task library limits the number of levels of derivation from class task to one. That is, a class derived from class task may not have derived classes. However, use of multilevel inheritance is not detected and usually results in an unexpected runtime core dump.

  One possible workaround for this limitation is to put the required complex structures in a class not derived from task. Then derive a trivial class from task whose constructor executes the coroutine in the complex task. For example:

```
class Task_base {
        virtual int Main();
};

class Runner : public task {
        Task_base*   p;
public:
        Runner(Task_base*);
};

Runner::Runner(Task_base* fp) : p(fp)
{
        resultis(p->Main());
}
```

  Class Task_base is the base class from which the user should derive whatever additional classes and structures are needed.

B Appendix B

Implementation Specific Behavior

This appendix describes implementation specific behavior of the C++ Language System. Implementation specific behaviors can be categorized as follows:

1. behavior that the *Reference Manual* defines as "implementation dependent"
2. behavior that depends on the underlying C compiler or preprocessor used with Release 3.0
3. properties that are defined in the standard header files `stddef.h`, `limits.h`, and `stdlib.h`
4. translation limits
5. language constructs that are not implemented in this release

This appendix addresses categories 1, 2, 4, and 5. For details about properties defined in the standard header files (category 3), see the headers themselves. Additional information about constructs that are not implemented is provided in Appendix C, which contains an alphabetical listing of the "not implemented" error messages.

The ordering and numbering of sections in this appendix corresponds to the order and numbering of the related sections in the *Reference Manual*. The section entitled "Translation Limits" (which does not have a corresponding section in the *Reference Manual*) precedes the numbered sections.

Translation Limits

Release 3.0 of the AT&T C++ Language System imposes the following translation limits:

- 50 nesting levels of compound statements
- 10 nesting levels of linkage declarations
- 4088 characters in a token
- 22222 virtual functions in a class
- 10000 identifiers generated by the implementation

These limits can be changed by recompiling the translator. Additional translation limits may be inherited from the underlying C compiler and preprocessor.

Identifiers (§2.3)

Identifiers reserved by Release 3.0: Release 3.0 reserves identifiers that contain a sequence of two underscores for its own use. In addition, identifiers reserved in the ANSI C standard are also reserved by Release 3.0. Under the +w option, identifiers with double underscores result in a warning in Release 3.0

Character Constants (§2.5.2)

Value of multicharacter constants: The *Reference Manual* states that the value of a multicharacter constant, such as `'abcd'`, is implementation dependent. Release 3.0 passes these constants to the underlying C compiler, which determines their values. A multicharacter constant containing more characters than `sizeof(int)` is reported as an error by Release 3.0.

Value of (single) character constants: The *Reference Manual* states that the value of a character constant is implementation dependent if it exceeds that of the largest `char`. Release 3.0 accepts octal and hexadecimal character literals that do not fit in a `char`. It uses the low order bits that make up the value of the constant. For example, the octal character constant `'\777'`, is treated as `'\377'`. The hexadecimal character constant `'\x123'` is treated as `'\x23'`.

Wide character constants: Release 3.0 does not implement wide character constants, such as `L'ab'`. A "not implemented" error message is reported.

Floating Constants (§2.5.3)

Long double floating constants: When compiling with the `+a0` option, Release 3.0 removes an `l` or `L` suffix from a floating constant before passing the constant to the underlying C compiler. Under the `+a1` option such a constant is passed unchanged to the underlying C compiler. In either case, the constant is considered to be of type `long double` for purposes of resolving overloaded function calls.

String Literals (§2.5.4)

Distinct string literals: The *Reference Manual* states that it is implementation dependent whether all string literals are distinct. Release 3.0 does not attempt to detect cases where string literals could be represented as overlapping objects. The underlying C compiler may, however, detect such cases and attempt to overlap their storage.

Wide character strings: Release 3.0 does not implement wide character strings, such as `L"abcd"`. A "not implemented" error message is reported.

Start and Termination (§3.4)

Type of main(): The *Reference Manual* states that the type of `main()` is implementation dependent. Release 3.0 itself does not impose any restrictions on the type of `main()`, but the underlying C compiler or the target environment may impose such restrictions.

Linkage of main(): The AT&T C++ Language System treats `main()` as if its linkage were `extern "C"`.

Fundamental Types (§3.6.1)

Signed integral types: Release 3.0 does not implement the type specifier `signed`; it issues a warning and proceeds as though the specifier `signed` had not appeared.

Long double type: When Release 3.0 is invoked with the `+a0` option, the type `long double` is considered to be the same size and precision as the type `double` in the underlying C compiler. Under the `+a1` option, `long double` is passed to the underlying C compiler as `long double`. In either case, type `long double` is considered a distinct type for purposes of resolving overloaded function declarations and invocations.

Alignment requirements: Release 3.0 does not impose any alignment restrictions when allocating objects of a particular type. Such restrictions, if they exist, are enforced by the underlying C compiler.

Integral Conversions (§4.2)

Conversion to a signed type: When a value of an integral type is converted to a signed integral type with fewer bits in the representation, Release 3.0 issues a warning message if the `+w` option is specified. The runtime behavior of such a conversion depends on the treatment of the conversion by the underlying C compiler.

Expressions (§5)

Overflow and divide check: The *Reference Manual* states that the handling of overflow and divide check in expression evaluation is implementation dependent. When the second operand of a division or modulus operator is known to be zero at compile time, Release 3.0 reports an error. Overflow and other divide check conditions are handled by the underlying C compiler and execution environment.

Function Call (§5.2.2)

Evaluation order: The *Reference Manual* states that the order of evaluation of arguments to a function call is implementation dependent; similarly, the order of evaluation of the postfix expression, which designates the function to be called, and the argument expression list are implementation dependent. In both cases the order depends on the treatment by the underlying C compiler.

Explicit Type Conversion (§5.4)

Explicit conversions between pointer and integral types: The *Reference Manual* states that the value obtained by explicitly converting a pointer to an integral type large enough to hold it is implementation dependent. This behavior is defined by the underlying C compiler. Similarly, the behavior when explicitly converting an integer to a pointer depends on the underlying C compiler.

Multiplicative Operators (§5.6)

Sign of the remainder: The *Reference Manual* states that the sign of the result of the modulus operator is non-negative if both operands are non-negative; otherwise, the sign of the result is implementation dependent. This behavior depends on the underlying C compiler except when the values of both operands are known at compile time. In this case, the sign of the result is the same as the sign of the numerator.

Shift Operators (§5.8)

Result of right shift: The *Reference Manual* states that the result of a right shift when the left operand is a signed type with a negative value is implementation dependent. This behavior depends on the underlying C compiler.

Relational Operators (§5.9)

Pointer comparisons: According to the *Reference Manual*, certain pointer comparisons are implementation dependent. For Release 3.0, the results of these comparisons depend on the underlying C compiler.

Storage Class Specifiers (§7.1.1)

Inline functions: The *Reference Manual* states that the `inline` specifier is a hint to the compiler. Chapter 8 of the *Selected Readings* describes the treatment of `inline` functions.

When compiling with the `+d` option, Release 3.0 always generates out-of-line calls to inline functions.

Type Specifiers (§7.1.6)

Volatile: Release 3.0 does not implement the type specifier `volatile`. If it is applied to a member function, a "not implemented" error message is issued; otherwise it is ignored and a warning message is issued.

Signed: Release 3.0 does not implement the type specifier `signed`; it is ignored and a warning message is issued.

Asm Declarations (§7.3)

Effect of an asm declaration: Release 3.0 passes `asm` declarations to the underlying C compiler without modification.

Linkage Specifications (§7.4)

Languages supported: Release 3.0 supports linkage to C and C++.

Linkage to functions: The effect of a `"C"` linkage specification (`extern "C"`) on a function that is not a member function is that the function name is not encoded with type information, as is otherwise done for C++ functions. Member functions are not affected by linkage specifications.

Linkage to non-functions: The C linkage specification (`extern "C"`), when applied to a non-function declaration, does not affect the C code generated.

Class Members (§9.2)

Allocation of non-static data members: The *Reference Manual* states that the order of allocation of non-static data members across *access-specifier*s is implementation dependent. Release 3.0 allocates non-static data members in declaration order.

Bit-Fields (§9.6)

Allocation and alignment of bit-fields: The *Reference Manual* states that the allocation and alignment of bit-fields within a class object is implementation dependent. Responsibility for the allocation and alignment of bit-fields rests with the underlying C compiler.

Sign of "plain" bit-fields: Whether the high-order bit position of a "plain" `int` bit-field is treated as a sign bit depends on the behavior of the underlying C compiler.

Multiple Base Classes (§10.1)

Allocation of base classes: The *Reference Manual* states that the order in which storage is allocated for base classes is implementation dependent. For non-virtual base classes, Release 3.0 allocates storage in the order that they are mentioned in the derived class declaration.

Argument Matching (§13.2)

Integral arguments: The type of the result of an integral promotion (§4.1) depends on the execution environment, as does the type of an unsuffixed integer constant (§2.5.1). Consequently, the determination of which overloaded function to call may also depend on the execution environment, as illustrated by an example in §13.2 of the *Reference Manual.*

Exception Handling (experimental) (§15)

Release 3.0 does not implement exception handling. The keyword `catch` is reserved for future use. A "not implemented" error message is reported if `catch` is seen.

Predefined Names (§16.10)

Predefined macros: The following macros are defined by Release 3.0:

`__cplusplus`	The decimal constant 1.
`c_plusplus`	The decimal constant 1. This macro is provided for compatibility with previous releases and will *not* be supported in the next major release.

Other macros may be predefined by the underlying preprocessor.

Anachronisms (§B.3)

For compatibility with previous releases, Release 3.0 supports the anachronisms described in Appendix B. These anachronisms will *not*, however, be supported in the next major release of the AT&T C++ Language System. The current and future behavior are described in Chapter 4 of the *Release Notes*.

C Appendix C

"Not Implemented" Messages

This appendix contains the text and explanation for all "not implemented" messages produced by the C++ Language System Release 3.0.1. They are listed here in alphabetical order.

Each message is preceded by a file name and line number. The line number is usually the line on which a problem has been diagnosed.

A "not implemented" message is issued when Release 3.0.1 encounters a *legal* construct for which it cannot generate code. Because code is not generated, "not implemented" messages cause the `CC` command to fail, and the program is not linked. Release 3.0.1 does, however, attempt to examine the rest of your program for other errors.

- `actual parameter expression of type string literal`

  A template is instantiated with a string literal actual argument:

  ```
  template <char* s> struct S {/*...*/};

  S<"hello world"> svar;
  ```

  ```
  "file", line 3: not implemented: actual parameter expression of type string literal
  ```

- `address of bound member as actual template argument`

  A template is instantiated with the address of a class member bound to an actual class object:

  ```
  template <int *pi> class x {};
  class y { public: int i; } b;

  x< &b.i > xi;
  ```

  ```
  "file", line 4: not implemented: address of bound member (& ::b . y::i) as actual
  template argument
  ```

- `& of` *op*

  This message should not be produced.

- `1st operand of .* too complicated`

  The first operand of a function call expression involves a pointer to a member function and is an expression that may have side effects or may require a temporary.

```
struct S { virtual int f(); };
int (S::*pmf)() = &S::f;
S *f();
int i = (f()->*pmf)();
```

```
"file", line 5: not implemented: 1st operand of .* too complicated
```

- `2nd operand of .* too complicated`

  The second operand of a pointer to member operator is an expression that has side effects.

```
struct S { int f(); };
int (S::*pmf)() = &S::f;
S *sp = new S;
int i = 5;
int j = (sp->*(i+=5, pmf))();
```

```
"file", line 5: not implemented: 2nd operand of .* too complicated
```

- `call of virtual function before class has been completely declared`

```
class x {
public:
    virtual x& f();
    int foo(x t = pt->f());
private:
    static x* pt;
    int i;
};
```

```
"file", line 6: not implemented:  call of virtual function x::f() before class x
has been completely declared - try moving call from argument list into function body or
make function non-virtual
```

- `cannot expand inline function with for statement`

  A `for` statement appears in the definition of an inline function.

```
struct S {
        int s[100];
        S() { for (int i = 0; i < 100; i++) s[i] = i; }
};
```

```
"file", line 1: not implemented: cannot expand inline function S::S() with
for statement in inline
```

- `cannot expand inline function with return statement`

  A void function contains a `return` statement.

```
inline void f()
{
        return;
}

main()
{
        f();
}
```

```
"file", line 8: not implemented: cannot expand inline function f() with  return statement
1 error
```

- `cannot expand inline function with statement after "return"`

  A value-returning inline function contains a statement following a `return` statement.

```
inline int f(int i) {
        if (i) return i;
        return 0;
}
```

```
"file", line 4: not implemented: cannot expand inline function f() with statement
after "return"
```

- `cannot expand inline function with two local variables with the same name`

  Two variables with the same name and different types are declared within the body of a value-returning inline function.

```
inline int f(int i) {
        { int x = i; }
        { double x = i; }
        return 0;
}
```

```
"file", line 5: not implemented: cannot expand inline function f() with two local
variables with the same name (x)
```

- `cannot expand inline function needing temporary variable of array type`

  An inline function that contains a local declaration of an array object is called.

```
inline int f(int i) {
        int a[1];
        a[0] = i;
        return i;
}
int v = f(0);
```

```
"file", line 6: not implemented: cannot expand inline function needing
temporary variable of array type
```

- `cannot expand inline function with return in if statement`

  This message should not be produced.

- `cannot expand inline function with static`

An inline function contains the declaration of a static object.

```
inline void f() {
        static int i = 5;
}
```

```
"file", line 2: not implemented: cannot expand inline function with static i
```

- `cast of non-integer constant`

  A cast of a non-integer constant as an actual parameter to a template class.

```
template <int i> class x;
int yy;

x< (int)&yy > xi;
```

```
"file", line 4: not implemented: cast of non-integer constant
```

- `cannot expand inline void` *function* `called in comma expression`

  A call of an `inline void` function that cannot be translated into an expression (that is, one that includes a loop, a `goto`, or a `switch` statement) appears as the first operand of a comma operator.

```
int i;
inline void f() { for (;;) ; }
void g() { for (f(), i = 0; i < 10; i++) ; }
```

```
"file", line 3: not implemented: cannot expand inline void f() called in
comma expression
```

- `cannot expand inline void` *function* `called in for expression`

  A call of an `inline void` function that cannot be translated into an expression (that is, one that includes a loop, a `goto`, or a `switch` statement) appears in the second expression of a `for` statement.

```
void inline f() { for (;;) ; }
void g() { for (;; f()) ; }
```

```
"file", line 2: not implemented: cannot expand inline void f() called in
for expression
```

- `cannot expand value-returning inline` *function* `with call of ...`

  A value-returning inline function is defined, and it contains a call to another inline function that is not value-returning.

  ```
  inline void f() { for(;;) ; }
  inline int g() { f(); return 0; }
  ```

```
"file", line 2: not implemented: cannot expand value-returning inline g() with
call of non-value-returning inline f()
```

- `cannot merge lists of conversion functions`

  A derived class with multiple bases is declared and there are conversion operators declared in more than one of the base classes.

  ```
  struct B1 {
          operator int();
  };
  struct B2 {
          operator float();
  };
  struct D : public B1, public B2 { };
  ```

```
"file", line 7: not implemented: cannot merge lists of conversion functions
```

- `catch`

  The keyword `catch` appears; `catch` is reserved for future use.

  ```
  int catch;
  ```

```
"file", line 1: not implemented: catch
"file", line 1: warning: name expected in declaration list
```

- `class defined within sizeof`

  A class or union definition appears as the type name in a `sizeof` expression.

  ```
  int i = sizeof (struct S { int i; });
  ```

```
"file", line 1: not implemented: class defined within sizeof
"file", line 1: error: S undefined, size not known
```

- `class hierarchy too complicated`

  This message should not be produced.

- `conditional expression with` *type*

  The second and third operands of a conditional expression are member functions or pointers to members.

  ```
  struct S { int i, j; };
  void f(int i) {
          int S::*pmi = i ? &S::i : &S::j;
  }
  ```

```
"file", line 3: not implemented: conditional expression with int S::*
```

- `constructor needed for argument initializer`

  The default value for an argument is a constructor or is an expression that invokes a constructor.

  ```
  struct S { S(int); };
  int f(S = S(1));
  int g(S = 5);
  ```

```
"file", line 2: not implemented: constructor as default argument
"file", line 3: not implemented: constructor needed for argument initializer
```

- `copy of` *member*`[], no memberwise copy for` *class*

  An implementation-generated copy operation for a class `X` is required, but the operation cannot be generated because `X` has an array member whose type is a class with either a virtual base class or its own defined copy operation. The workaround is to add a memberwise copy operator to `X`.

```
struct S1 {};
struct S2 : S1 { S2& operator=(const S2&); };
struct X { S2 m[1]; };
X var1;
X var2 = var1;
```

```
"file", line 5: not implemented: copy of S2[], no memberwise copy for S2
```

- `default argument too complicated`

  A default argument in a declaration not at file scope requires the generation of a temporary.

```
struct S {
        S();
        int f(const int &r = 1);
};
```

```
"file", line 3: not implemented: default argument too complicated
"file", line 3: not implemented: needs temporary variable to evaluate argument
initializer
```

- `ellipsis (...) in argument list of template function` *name*

  An ellipsis is used in a template function declaration:

```
template <class T> f(T, ...);
```

```
"file", line 1: not implemented: ellipsis (...) in argument list of template function f()
```

- `explicit template parameter list for destructor of specialized template class` *name*

  Explicit template parameters are included in declaration of a specialized class' destructor:

```
template <class T> struct S { /*...*/ };

struct S<int> {
      ~S<int>();
};
```

```
"file", line 4: not implemented: explicit template parameter list for destructor
of specialized template class  S <> -- please drop the parameter list
```

Instead, declare the specialized destructor as follows:

```
template <class T> struct S { /*...*/ };

struct S<int> {
      ~S();
};
```

- `formal type parameter` *name* `used as base class of template`

  The formal type parameter is used as the base class of a template class:

```
template <class T> struct S : public T {/*...*/};
```

```
"file", line 1: not implemented: formal type parameter T used as base class of template
```

- `forward declaration of a specialized version of template` *name*

  A forward declaration of a specialized, rather than generalized template:

```
template <class T> struct S;
struct S<int>;
```

```
"file", line 2: not implemented: forward declaration of a specialized version of
template S <int >
```

- `general initializer in initializer list`

  The initializer list in a declaration contains an expression that cannot easily be evaluated at compile time or that requires runtime evaluation.

  ```
  int f();
  int i[1] = { f() };
  ```

  ```
  "file", line 2: not implemented: general initializer in initializer list
  ```

- `initialization of` *name* `(automatic aggregate)`

  An aggregate at local scope is initialized. This message is not issued if the `+a1` option (produces declarations acceptable to an ANSI C compiler) is specified.

  ```
  void f() {
        int i[1] = {1};
  }
  ```

  ```
  "file", line 2: not implemented: initialization of i (automatic aggregate)
  ```

- `initialization of union with initializer list`

  An object of union type is initialized with an initializer list. This message is not issued if the `+a1` option (produces declarations acceptable to an ANSI C compiler) is specified.

  ```
  union U { int i; float f; };
  U u = {1};
  ```

```
"file", line 2: not implemented: initialization of union with initializer list
```

- `initializer for class member array with constructor`

  This message should always be accompanied by an error message. The "not implemented" message is inappropriate and should not be reported.

- `initializer for local static too complicated`

  This message should not be produced.

- `initializer for multi-dimensional array of objects of class` *class* `with constructor` *name*

  A multi-dimensional array of a class with a constructor has an explicit initializer.

```
struct S { S(int); };
S s[2][2] = {1,2,3,4};
```

```
"file", line 2: not implemented: initializer for multi-dimensional
array of objects of class S with constructor ::s
```

- `implicit static initializer for multi-dimensional array of objects of class with constructor`

```
class x {
public:
        x() ;
};

main() {
static x xx[10][20];
}
```

```
"file", line 7: not implemented: implicit static initializer for multi-dimensional
array of objects of class x with constructor
```

- `initializer list for local variable` *name*

  This message should not be produced.

- `label in block with destructors`

  A labeled statement appears in a block in which an object with a destructor exists.

```
struct S { S(int); ~S(); };
void f() {
      S s(5);
xyz:  ;
}
```

```
"file", line 5: not implemented: label in block with destructors
```

- `local class` *class*`(local to` *function*`) as parameter to template class` *class*

  A local class is defined and is used as a template actual argument.

```
template <class T> class A {};

void f()
{
      class B {};
      A<B> a;
}
```

```
"file", line 6: not implemented: local class B(local to f()) as parameter type to
template class A
```

- `local class` *name* `within template function`

  A local class is defined inside a template function. A similar message is issued for `local` enums and `local` typedefs defined inside a template function:

```
template <class T> f() {
      class l {/*...*/};
      enum E {/*...*/};
      typedef int* ip;
};
```

```
"file", line 2: not implemented: local class l (local to f()) within template function
"file", line 3: not implemented: local enum E(local to f()) within template function
"file", line 4: not implemented: local typedef ip within template function
```

- `local static class` *name* `(` *type* `)`

  A static array of objects of a class with a constructor is declared at local scope.

```
class S {
public:
       S();
};
void f() {
       static S s[9];
}
```

```
"file", line 2: not implemented: local static class s ( S [9])
```

- `local static` *name* `has` *class*`::~`*class*`() but no constructor (add` *class*`::` *class*`())`

  A static class object with a destructor, but no constructor, appears at local scope.

```
struct S { ~S(); };
void f() { static S s; }
```

```
"file", line 1: warning: S has S::~S() but no constructor
"file", line 2: not implemented: local static s has S::~S() but no constructor
(add S:: S())
```

- `lvalue` *op* `too complicated`

  This message should not be produced.

- `needs temporary variable to evaluate argument initializer`

  A default argument requires a temporary variable.

```
void f() {
      int g(const int& = 5);
}
```

```
"file", line 2: not implemented: needs temporary variable to evaluate argument
initializer
```

- `nested class` ***type*** `as parameter type to template class` ***name***

  A nested class is used as the actual parameter for a template class instantiation:

```
template <class T> struct S;

struct outer {
      struct inner {};
};

S<outer::inner> svar;
```

```
"file", line 7: not implemented: nested class outer::inner as parameter type to
template class S
```

- `nested class within template`

  A template class contains a nested class.

```
template <class T> struct A {
      struct B {};
};
```

```
"file", line 2:  not implemented: nested class within template
```

- `nested depth class beyond 9 unsupported`

  Classes are nested more than nine levels deep.

```
struct S1 {
 struct S2 {
  struct S3 {
   struct S4 {
    struct S5 {
     struct S6 {
      struct S7 {
       struct S8 {
        struct S9 {
         struct S10 { enum { e }; };
};};};};};};};};};
```

```
"file", line 20: not implemented: nested depth class beyond  9 unsupported
```

- `nested enum` *enum* `in template specialization`
- `nested typedef` *typedef* `in template specialization`

  A nested enum or typedef is used in a template specialization.

```
template <class T> struct A {
       enum E {ee = sizeof(T)};
       typedef T T2;
};

struct A<int> {
       enum E {ee = 47};
       typedef int T2;
};
```

```
"file", line 13: sorry, not implemented: nested enum E in template specialization
"file", line 14: sorry, not implemented: nested typedef T2 in template specialization
```

- `non-trivial declaration in switch statement`

  A "non-trivial" declaration appears within a switch statement. Such a declaration might declare an object of reference type, a static object, a `const` object, an object of a class type with constructor or destructor, an object with an initializer list, or an object initialized with a string literal.

```
void f(int i) {
        switch (i) {
        default:
                int& j = i;
        }
}
```

```
"file", line 2: not implemented: non-trivial declaration in switch statement
(try enclosing it in a block)
```

Note that since it is illegal to jump past a declaration with an explicit or implicit initializer unless the declaration is in an inner block that is not entered, most declarations in `switch` statements and not contained in inner blocks will be errors.

- `overly complex` *op* `of` *op*

  This message should not be produced.

- `parameter expression of type float, double or long double`

  A template taking a non-type argument is declared taking a float, double or long double argument:

  ```
  template <double d> struct S { /*...*/};
  ```

  ```
  "file", line 1: not implemented:  parameter expression of type float, double, or long double
  ```

- `postfix template function operator ++(): please make a class member function`

  The postfix implementation of a template increment or decrement operator must be a member function.

  ```
  template <class t> struct x {
        int operator++(int); // ok
  };

  template <class t>
       int operator++(x<t>&,int); // sorry

  x<int> xi;
  ```

```
"file", "", line 6: not implemented: postfix template function operator ++():
please make a class member function
```

- `pointer to member function` *type* `too complicated`

  This message should not be produced.

- `public specification of overloaded` *function*

  The base class member in an access declaration refers to an overloaded function. A similar message is issued for `private` and `protected` access declarations.

```
struct B { int f(); int f(int); };
class D : private B {
public:
        B::f;
};
```

```
"file", line 2: not implemented: public specification of overloaded B::f()
```

- `reuse of formal template parameter` *name*

  A template formal parameter name is reused within the template declaration:

```
template <class T> struct S {
      int T;
};
```

```
"file", line 2: not implemented: reuse of formal template parameter T
```

- `specialized template` *name* `not at global scope`

  A specialized template is declared at other than global scope:

```
template <class T> struct S {
      T var;
};

void f() {
      struct S <int > {
            int var;
      };

};
```

```
"file", line 6: not implemented: specialized template S not at global scope
```

- static member anonymous union

  A static class member is declared as an anonymous union.

```
class C {
      static union {
            int i;
            double d;
      } ;
};
```

```
"file, line 5: not implemented: static member anonymous union
```

- struct *name* member *name*

  This message should not be produced.

- template function instantiated with local class *name*

```
template <class T> int f(T);

f2() {
      struct local {/*...*/};
      local lvar;
      f(lvar);
}
```

```
"file", line 6: not implemented:  template function f() instantiated with local class local
```

- `temporary of class` *name* `with destructor needed in` *expr* `expression`

  An expression containing a `?:`, `||`, or `&&` operator requires a temporary object of a class that has a destructor.

```
struct S { S(int); ~S(); };
S f(int i) {
        return i ? S(1) : S(2) ;
}
```

```
"file", line 3: not implemented: temporary of class S with destructor needed
in ?: expression
```

- `too few initializers for` *name*

  The initializer list for an array of class objects has fewer initializers than the number of elements in the array.

```
struct S { S(int); S(); };
S a[2] = {1};
```

```
"file", line 2: not implemented: too few initializers for ::a
```

- *type1* `assigned to` *type2* `(too complicated)`

  A pointer is initialized or assigned with an expression whose type is too complicated.

```
struct S1 {};
struct S2 { int i; };
struct S3 : S1, S2 {};
int S3::*pmi = &S2::i;
```

```
"file", line 4: not implemented: int S2::* assigned to int S3::* (too complicated)
```

- use of *member* with formal template parameter

  An attempt to use a member of a formal parameter type, such as `T::type`, is not currently supported. For example,

```
template <class T> class U
{
        typedef T TU;
        // ...
};

template <class Type> class V
{
        Type::TU t;
        // ...
};
```

```
"file", line 9: not implemented: use of  Type::TU  with formal template type parameter
"file", line 9: cannot recover from earlier errors
```

- variant nested enum *enum* in template
- variant nested typedef *typedef* in template

  A variable enum or typedef is declared in a template definition.

```
template <class T> struct A {
        enum E {ee = sizeof(T)};
        typedef T T2;
};

main()
{
        A<char>       a;
}
```

```
"file", line 2: sorry, not implemented: variant nested enum E in template
"file", line 2:    error detected during the instantiation of A <char >
"file", line 9:    is the site of the instantiation
"file", line 3: sorry, not implemented: variant nested typedef T2 in template
"file", line 3:    error detected during the instantiation of A <char >
"file", line 9:    is the site of the instantiation
```

- `visibility declaration for conversion operator`

  An access declaration is specified for a conversion operator.

```
struct B { operator int(); };
class D : private B {
public:
        B::operator int;
};
```

```
"file", line 1: not implemented: visibility declaration for conversion operator
```

- `volatile functions`

  A member function is specified as `volatile`.

```
struct S {
        int f() volatile;
};
```

```
"file", line 2: not implemented: volatile functions
```

- `wide character constant`
- `wide character string`

  A wide character constant or a wide character string is used.

```
int wc = L'ab';
char *ws = L"abcd";
```

```
"file", line 1: not implemented: wide character constant
"file", line 2: not implemented: wide character string
```

D

Manual Pages

To see the online man page for *CC(1)*, type man CC.

Man pages are provided online for the following commands:

- *CC(1)*
- *c++filt(1)*
- *demangle(3)*

NAME

c++filt – C++ name demangler

SYNOPSIS

`c++filt [-m] [-s] [-v]`

DESCRIPTION

`C++filt` copies standard input to standard output after decoding tokens which look like C++ encoded symbols. Any combination of the following options may be used:

`-m`	Produce a symbol map on standard output. This map contains a list of the encoded names encountered and the corresponding decoded names. This output follows the filtered output.
`-s`	Produce a side-by-side decoding with each encoded symbol encountered in the input stream replaced by the decoded name followed by the original encoded name.
`-v`	Output a message giving information about the version of `c++filt` being used.

SEE ALSO

`CC`(1), `ld`(1), `nm`(1).

NAME

`elf_demangle` – decode a C++ encoded symbol name

SYNOPSIS

```
char *elf_demangle (char const *symbol)
```

DESCRIPTION

`demangle` decodes an encoded C++ symbol name into a format which more closely resembles the original C++ declaration. This routine should be used to convert symbols obtained from an ELF symbol table into a form more suitable for output.

WARNING

This routine allocates space for the return buffer using the ELF allocation routines.

CAVEAT

The return value points to static data whose content is overwritten by each call.

SEE ALSO

`CC`(1), `c++filt`(1), `libelf`(3), `nm`(1).
Bjarne Stroustrup, *The C++ Programming Language,* Addison-Wesley 1986.

DIAGNOSTICS

The argument `symbol` will be returned if it points to a string which does not need decoding. A return value of `NULL` indicates that storage could not be allocated for the return buffer.

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C++ Language System Release 3.0

Library Manual

Contents

Figures and Tables

Preface

Preface

The C++ *Language System Library Manual* describes the C++ class libraries provided with Release 3.0 of the C++ Language System:

- the complex arithmetic library
- the task library
- the iostream library

The manual is part of a set of four documents that are supplied with your C++ Language System. The other documents are:

- the *Release Notes*, which describe the contents of this release, how to install it, and changes to the language
- the *Product Reference Manual*, which provides a complete definition of the C++ language supported by Release 3.0 of the Language System.
- the *Selected Readings*, which contains papers describing aspects of the C++ language

The chapters in this manual cover the following C++ class libraries:

- Chapter 1 describes the complex arithmetic library, which provides a class `complex` that allows you to declare and manipulate complex numbers in C++ programs
- Chapter 2 describes the task library, which allows you to create and control concurrent processes in C++ programs. The last section of Chapter 2 provides porting information for the task library, which is machine dependent.
- Chapter 3 describes the stream library, which allows you to do formatted input and output from C++ programs
- The back of this book contains manual pages for the complex library, task library, and iostream library.

To make the best use of the *Library Manual,* you must be familiar with the C programming language and the C programming environment under the UNIX operating system.

Acknowledgements

- Chapter 1 is based on the paper, "Complex Arithmetic in C++," by Leonie V. Rose and Bjarne Stroustrup. That paper acknowledges the following contributions:

  Phil Gillis supplied us with the complex functions used for the cxp package. Most of the functions presented here are modified versions of those. Stu Feldman provided us with valuable advice and some functions. Doug McIlroy's constructive comments led to a major rewrite. Eric Grosse suggested the FFT function as an example.

- Chapter 2 is based on papers by Bjarne Stroustrup, Jonathan Shopiro, and Stacey Keenan:

  - The first section is taken from "A Set of C++ Classes for Co-routine Style Programming," by Bjarne Stroustrup and Jonathan Shopiro, which was originally published in the Proceedings of the USENIX C++ Workshop, November, 1987. That paper acknowledges the following contributions:

    The task system is in many ways a descendant of A.G. Fraser's set of C functions described in the paper "C Language Routines for Multi-Thread Computation," Bell Telephone Laboratories Internal Memorandum, 1979. M.D. McIlroy acted as "midwife" for many parts of the design.

  - The second section is taken from "Extending the C++ Class System for Real-Time Control," by Jonathan Shopiro. That paper acknowledges the following contributions:

    The original task system was developed by Bjarne Stroustrup, and the original port to the 68000 was done by Rafael Bracho. This work was begun as an attempt to examine concurrency features of Concurrent C and those of the C++ task system by translating a robot control system developed in Concurrent C by Ingemar Cox, whose help is much appreciated. Also useful were conversations with Thomas Cargill and Bart Locanthi.

  - The third section is taken from "A Porting Guide for the C++ Coroutine Library," by Stacey Keenan.

- Chapter 3 is based on the paper "Iostream Examples," by Jerry Schwarz.

1 Complex Arithmetic in C++

Complex Arithmetic in C++

NOTE

This chapter is taken directly from a paper by Leonie V. Rose and Bjarne Stroustrup.

Abstract

This memo describes a data type `complex` providing the basic facilities for using complex arithmetic in C++. The usual arithmetic operators can be used on complex numbers and a library of standard complex mathematical functions is provided. For example:

```
#include <complex.h>

main(){
        complex xx;
        complex yy = complex(1,2.718);
        xx = log(yy/3);
        cout << 1+xx;
}
```

initializes `yy` as a complex number of the form `(real+imag*i)`, evaluates the expressions and prints the result: `(0.96476,1.21825)`.

The data type `complex` is implemented as a class using the data abstraction facilities in C++. The arithmetic operators +, –, *, and /, the assignment operators =, +=, –=, *=, and /=, and the comparison operators == and != are provided for complex numbers. So are the trigonometric and mathematical functions: `sin()`, `cos()`, `cosh()`, `sinh()`, `sqrt()`, `log()`, `exp()`, `conj()`, `arg()`, `abs()`, `norm()`, and `pow()`. Expressions such as `(xx+1)*log(yy*log(3.2))` that involve a mixture of real and complex numbers are handled correctly. The simplest complex operations, for example + and +=, are implemented without function call overhead.

Introduction

The C++ language does not have a built-in data type for complex numbers, but it does provide language facilities for defining new data types. The type `complex` was designed as a useful demonstration of the power of these facilities.

There are three plausible ways to support complex numbers in a language. First, the type `complex` could be directly supported by the compiler in the same way as the types `int` and `float` are. Alternatively, a preprocessor could be written to translate all use of complex numbers into expressions involving only built-in data types. A third approach was used to implement type `complex`; it was specified as a user-defined type. This demonstrates that one can achieve the elegance and most of the efficiency of a built in data type without modifying the compiler. It is even much easier to implement than the pre-processor approach, which is likely to provide an inferior user interface.

This facility for complex arithmetic provides the arithmetic operators `+`, `/`, `*`, and `–`, the assignment operators `=`, `+=`, `–=`, `*=`, and `/=`, and the comparison operators `==` and `!=` for complex numbers. Input and output can be done using the operators >> (get from) and << (put to). The initialization functions and >> accept a Cartesian representation of a `complex`. The functions `real()` and `imag()` return the real and imaginary part of a `complex`, respectively, and << prints a `complex` as `(real,imaginary)`. The internal representation of a `complex`, is, however, inaccessible and in principle unknown to a user. Polar coordinates can also be used. The function `polar()` creates a `complex` given its polar representation, and `abs()` and `arg()` return the polar magnitude and angle, respectively, of a `complex`. The function `norm()` returns the square of the magnitude of a `complex`. The following complex functions are also provided: `sqrt()`, `exp()`, `log()`, `sin()`, `cos()`, `sinh()`, `cosh()`, `pow()`, and `conj()`. The declaration of `complex` and the declarations of the complex functions can be found under "Type `complex`." A complete program using complex numbers can be found under "An FFT Function."

Complex Variables and Data Initialization

A program using complex arithmetic will contain declarations of `complex` variables. For example:

```
complex zz = complex(3,-5);
```

will declare `zz` to be complex and initialize it with a pair of values. The first value of the pair is taken as the real part of the Cartesian representation of a complex number and the second as the imaginary part. The function `complex()` constructs a complex value given suitable arguments.[1] It is responsible for initializing `complex` variables, and will convert the arguments to the proper type `(double)`. Such initializations may be written more compactly. For example:

```
complex zz(3,-5);
complex c_name(-3.9,7);
complex rpr(SQRT_2,root3);
```

A complex variable can be initialized to a real value by using the constructor with only one argument. For example:

```
complex ra = complex(1);
```

will set up `ra` as a complex variable initialized to `(1,0)`. Alternatively the initialization to a real value can also be written without explicit use of the constructor:

```
complex rb = 123;
```

The integer value will be converted to the equivalent complex value exactly as if the constructor `complex(123)` had been used explicitly. However, no conversion of a `complex` into a `double` is defined, so

```
double dd = complex(1,0);
```

is illegal and will cause a compile time error.

If there is no initialization in the declaration of a complex variable, then the variable is initialized to `(0,0)`. For example:

```
complex orig;
```

is equivalent to the declaration:

```
complex orig = complex(0,0);
```

Naturally a complex variable can also be initialized by a complex expression. For example:

```
complex cx(-0.5000000e+02,0.8660254e+02);
complex cy = cx+log(cx);
```

It is also possible to declare arrays of complex numbers. For example:

```
complex carray[30];
```

sets up an array of 30 complex numbers, all initialized to `(0,0)`. Using the above declarations:

```
complex carr[] = { cx, cy, carray[2], complex(1.1,2.2) };
```

sets up a complex array `carr[ ]` of four `complex` elements and initializes it with the members of the list. However, a struct style initialization cannot be used. For example:

```
complex cwrong[] = {1.5, 3.3, 4.2, 4};
```

is illegal, because it makes unwarranted assumptions about the representation of complex numbers.

Input and Output

Simple input and output can be done using the operators >> (get from) and << (put to). They are declared like this using the facility for overloading function operators:

```
ostream& operator<<(ostream&, complex);
istream& operator>>(istream&, complex&);
```

When `zz` is a complex variable `cin>>zz` reads a pair of numbers from the standard input stream `cin` into `zz`. The first number of the pair is interpreted as the real part of the Cartesian representation of a complex number and the second as the imaginary part. The expression `cout<<zz` writes `zz` to the standard output stream `cout`. For example:

```
void copy(istream& from, ostream& to)
{
        complex zz;
        while (from>>zz) to<<zz;
}
```

reads a stream of complex numbers like `(3.400000,5.000000)` and writes them like `(3.4,5)`. The parentheses and comma are mandatory delimiters for input, while white space is optional. A single real number, for example `10e-7` or `(123)`, will be interpreted as a `complex` with `0` as the imaginary part by operator >>.

A user who does not like the standard implementation of << and >> can provide alternate versions.

Cartesian and Polar Coordinates

The functions `real()` and `imag()` return the real and imaginary parts of a complex number, respectively. This can, for example, be used to create differently formatted output of a `complex`:

```
complex cc = complex(3.4,5);
cout << real(cc) << "+" << imag(cc) << "*i";
```

will print `3.4+5*i`.

The function `polar()` creates a `complex` given a pair of polar coordinates (magnitude, angle). The functions `arg()` and `abs()` both take a `complex` argument and return the angle and magnitude (modulus), respectively. For example:

```
complex cc = polar(SQRT_2,PI/4);      // also known as complex(1,1)
double magn = abs(cc);                // magn = sqrt(2)
double angl = arg(cc);                // angl = PI/4
cout << "(m=" << magn << ", a=" << angl << ")";
```

If input and output functions for the polar representation of complex numbers are needed they can easily be written by the user.

Arithmetic Operators

The basic arithmetic operators +, − (unary and binary), /, and *, the assignment operators =, +=, −=, *=, and /=, as well as the equality operators == and `!=`, can be used for complex numbers. The operators have their conventional precedences. For example: `a=b*c+d` for complex variables `a`, `b`, `c`, and `d` is equivalent to `a=(b*c)+d`. There are no operators for exponentiation and conjugation; instead the functions `pow()` and `conj()` are provided. The operators +=, −=, *=, and /= do not produce a value that can be used in an expression; thus the following examples will cause compile time errors:

```
complex a, b;
// ...
if ( (a+=2)==0 ) {
        // ...
}
b = a *= b;
```

Mixed Mode Arithmetic

Mixed mode expressions are handled correctly. Real values will be converted to complex where necessary. For example:

```
complex xx(3.5,4.0);
complex yy = log(yy) + log(3.2);
```

This expression involves a mixture of real values: `log(3.2)`, and complex values: `log(yy)` and the sum. Another example of mixing real and complex, `xx=1`, is equivalent to `xx=complex(1)` which in turn is equivalent to `xx=complex(1,0)`. The interpretation of the expression `(xx+1)*yy*3.2` is `(((xx+complex(1))*yy)*complex(3.2))`.

Mathematical Functions

A library of complex mathematical functions is provided. A complex function typically has a counterpart of the same name in the standard mathematical library. In this case the function name will be overloaded. That is, when called, the function to be invoked will be chosen based on the argument type. For example, `log(1)` will invoke the real `log()`, and `log(complex(1))` will invoke the complex `log()`. In each case the integer `1` is converted to the real value `1.0`.

These functions will produce a result for every possible argument. If it is not possible to produce a mathematically acceptable result, the function `complex_error()` will be called and some suitable value returned. In particular, the functions try to avoid actual overflow, calling `complex_error()` with an overflow message instead. The user can supply `complex_error()`. Otherwise a function that simply sets the integer `errno` is used. See "Errors and Error Handling" for details.

```
complex conj(complex);
```

`Conj(zz)` returns the complex conjugate of `zz`.

```
double norm(complex);
```

`Norm(zz)` returns the square of the magnitude of `zz`. It is faster than `abs(zz)`, but more likely to cause an overflow error. It is intended for comparisons of magnitudes.

```
double   pow(double, double);
complex  pow(double, complex);
complex  pow(complex, int);
complex  pow(complex, double);
complex  pow(complex, complex);
```

`Pow(aa,bb)` raises `aa` to the power of `bb`. For example, to calculate `(1-i)**4`:

```
cout << pow( complex(1,-1), 4);
```

The output is `(-4,0)`.

```
double   log(double);
complex  log(complex);
```

`Log(zz)` computes the natural logarithm of `zz`. `Log(0)`, causes an error, and a huge value is returned.

```
double   exp(double);
complex  exp(complex);
```

`Exp(zz)` computes `e**zz`, `e` being 2.718281828...

```
double   sqrt(double);
complex  sqrt(complex);
```

`Sqrt(zz)` calculates the square root of `zz`.

The trigonometric functions available are:

```
double   sin(double);
complex  sin(complex);


double   cos(double);
complex  cos(complex);
```

Hyperbolic functions are also available:

```
double   sinh(double);
complex  sinh(complex);


double   cosh(double);
complex  cosh(complex);
```

Other trigonometric and hyperbolic functions, for example `tan()` and `tanh()`, can be written by the user using overloaded function names.

Efficiency

C++'s facility for overloading function names allows `complex` to handle overloaded function calls in an efficient manner. If a function name is declared to be overloaded, and that name is invoked in a function call, then the declaration list for that function is scanned in order, and the first occurrence of the appropriate function with matching arguments will be invoked. For example, consider the exponential function:

```
double   exp(double);
complex  exp(complex);
```

When called with a `double` argument the first, and in this case most efficient, `exp()` will be invoked. If a `complex` result is needed, the `double` result is then implicitly converted using the appropriate constructor.

For example:

```
complex foo = exp(3.5);
```

is evaluated as

```
complex foo = complex( exp(3.5) );
```

and not

```
complex foo = exp( complex(3.5) );
```

Constructors can also be used explicitly. For example:

```
complex add(complex a1, complex a2)          // silly way of doing a1+a2
{
        return complex( real(a1)+real(a2), imag(a1)+imag(a2) );
}
```

Inline functions are used to avoid function call overhead for the simplest operations, for example, `conj()`, `+`, `+=`, and the constructors (See "Type `complex`").

Type `complex`

This is the definition of type `complex`. It can be included as `<complex.h>`. A `friend` declaration specifies that a function may access the internal representation of a `complex`. The standard header file `<stream.h>` is included to allow declaration of the stream I/O operators << and >> for complex numbers.

```
#include <stream.h>
#include <errno.h>
#include <math.h>


class complex {
        double  re, im;
public:
         complex() { re=im=0; }
        complex(double r = 0, double i) { re=r; im=i; }

        friend  double  abs(complex);
        friend  double  norm(complex);
        friend  double  arg(complex);
        friend  complex conj(complex);
        friend  complex cos(complex);
        friend  complex cosh(complex);
        friend  complex exp(complex);
        friend  double  imag(complex);
        friend  complex log(complex);
        friend  complex pow(double, complex);
        friend  complex pow(complex, int);
        friend  complex pow(complex, double);
        friend  complex pow(complex, complex);
        friend  complex polar(double, double = 0);
        friend  double  real(complex);
        friend  complex sin(complex);
        friend  complex sinh(complex);
        friend  complex sqrt(complex);

        friend  complex operator+(complex, complex);
        friend  complex operator-(complex);
        friend  complex operator-(complex, complex);
        friend  complex operator*(complex, complex);
        friend  complex operator/(complex, complex);
        friend  int     operator==(complex, complex);
        friend  int     operator!=(complex, complex);

        void operator+=(complex);
        void operator-=(complex);
        void operator*=(complex);
        void operator/=(complex);
};


ostream& operator<<(ostream&, complex);
istream& operator>>(istream&, complex&);

inline complex operator+(complex a1, complex a2)
{
        return complex(a1.re+a2.re, a1.im+a2.im);
}

inline complex operator-(complex a1,complex a2)
{
        return complex(a1.re-a2.re, a1.im-a2.im);
}

inline complex operator-(complex a)
{
        return complex(-a.re, a.im);
}

inline complex conj(complex a)
{
        return complex(a.re, -a.im);
```

```
}

inline int operator==(complex a, complex b)
{
        return (a.re==b.re && a.im==b.im);
}

inline int operator!=(complex a, complex b)
{
        return (a.re!=b.re || a.im!=b.im);
}

inline void complex.operator+=(complex a)
{
        re += a.re;
        im += a.im;
}

inline void complex.operator-=(complex a)
{
        re -= a.re;
        im -= a.im;
}
```

An FFT Function

Transcribed from Fortran as presented in "FFT as Nested Multiplication, with a Twist" by Carl de Boor in SIAM Sci. Stat. Comput., Vol 1 No 1, March 1980.

```
#include <complex.h>

void fftstp(complex*, int, int, int, complex*);

const NEXTMX = 12;
int prime[NEXTMX] = { 2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37 };

complex* fft(complex *z1, complex *z2, int n, int inzee)
/*
        Construct the discrete Fourier transform of z1 (or z2) in the
        Cooley-Tukey way, but with a twist.

        z1[before], z2[before].
        inzee==1 means input in z1; inzee==2 means input in z2
*/
{
        int before = n;
        int after = 1;
        int next = 0;
        int now;

        do {
                int np = prime[next];
                if ( (before/np)*np < before ) {
                        if (++next < NEXTMX) continue;
                        now = before;
                        before = 1;
                }
                else {
                        now = np;
                        before /= np;
                }
                if (inzee == 1)
                        fftstp(z1, after, now, before, z2);
                else
                        fftstp(z2, after, now, before, z1);
                inzee = 3 - inzee;
                after *= now;
        } while (1 < before)

        return (inzee==1) ? z1 : z2;
}


void fftstp(complex* zin, int after, int now, int before, complex* zout)
/*
```

```
            zin(after,before,now)
            zout(after,now,before)

            there is ample scope for optimization
    */
    {
        double angle = PI2/(now*after);
        complex omega = complex(cos(angle), -sin(angle));
        complex arg = 1;
        for (int j=0; j<now; j++) {
            for (int ia=0; ia<after; ia++) {
                for (int ib=0; ib<before; ib++) {
                        // value = zin(ia,ib,now)
                    complex value = zin[ia + ib*after + (now-1)*before*after];

                    for (int in=now-2; 0<=in; in--) {
                     // value = value*arg + zin(ia,ib,in)
                        value *= arg;
                        value += zin[ia + ib*after + in*before*after];
                    }
                 // zout(ia,j,ib) = value
                    zout[ia + j*after + ib*now*after] = value;
                }
                arg *= omega;
            }
        }
    }
```

The main program below calls `fft()` with a sine curve as argument. The complete unedited output is presented on the next page. All but two of the numbers ought to have been zero. The very small numbers shows the roundoff errors. Since C++ floating-point arithmetic is done in double-precision these errors are smaller than the equivalent errors obtained using the published Fortran version.

```
#include <complex.h>

extern complex* fft(complex*, complex*, int, int);

main()
/*
        test fft() with a sine curve
*/
{
        const n = 26;
        complex* z1 = new complex[n];
        complex* z2 = new complex[n];

        cout << "input: \m";
        for (int i=0; i<n ;i++) {
                z1[i] = sin(i*PI2/n);
                cout << z1[i] << "\m";
        }

        errno = 0;
        complex* zout = fft(z1, z2, n, 1);
        if (errno) cerr << "Cerror " << errno << " occurred\m";

        cout << "output: \m";
        for (int j=0; j<n ;j++) cout << zout[j] << "\m";
}
```

```
input:
(0, 0)
(0.239316, 0)
(0.464723, 0)
(0.663123, 0)
(0.822984, 0)
(0.935016, 0)
(0.992709, 0)
(0.992709, 0)
(0.935016, 0)
(0.822984, 0)
(0.663123, 0)
(0.464723, 0)
(0.239316, 0)
(4.35984e-17, 0)
(-0.239316, 0)
(-0.464723, 0)
(-0.663123, 0)
```

```
(-0.822984, 0)
(-0.935016, 0)
(-0.992709, 0)
(-0.992709, 0)
(-0.935016, 0)
(-0.822984, 0)
(-0.663123, 0)
(-0.464723, 0)
(-0.239316, 0)
output:
(9.56401e-17, 0)
(-3.76665e-16, -13)
(9.39828e-17, 1.11261e-17)
(6.42219e-16, -4.20613e-17)
(7.37279e-17, 2.33319e-16)
(2.85084e-16, 2.87918e-16)
(4.03134e-17, 5.1789e-17)
(2.60865e-16, 6.78794e-17)
(-5.71667e-17, -3.86348e-17)
(2.76315e-16, 2.36902e-17)
(-6.43755e-17, -3.80255e-17)
(1.95031e-16, 9.77858e-17)
(1.49087e-16, -7.57345e-17)
(3.17224e-16, 1.64294e-17)
(1.49087e-16, 7.57345e-17)
(2.7218e-16, -4.03777e-17)
(-6.43755e-17, 3.80255e-17)
(4.93805e-16, 3.36874e-17)
(-5.71667e-17, 3.86348e-17)
(7.86047e-16, -4.11068e-18)
(4.03134e-17, -5.1789e-17)
(1.60788e-15, -1.06841e-16)
(7.37279e-17, -2.33319e-16)
(5.45186e-15, 2.42719e-16)
(9.39828e-17, -1.11261e-17)
(-1.12013e-14, 13)
```

Errors and Error Handling

These are the declarations used by the error handling:

```
int errno;
int complex_error(int, double);
```

The user can supply `complex_error()`. Otherwise a function that simply sets `errno` is used. The exceptions generated are:

`cosh(zz):`	
`C_COSH_RE`	| zz.re | too large. Value with correct angle and huge magnitude returned.
`C_COSH_IM`	| zz.im | too large. Complex(0,0) returned.
`exp(zz):`	
`C_EXP_RE_POS`	zz.im too small. Value with correct angle and huge magnitude returned.
`C_EXP_RE_NEG`	zz.re too small. Complex(0,0) returned.
`C_EXP_IM`	| zz.im | too large. Complex(0,0) returned.
`log(zz):`	
`C_LOG_0`	zz==0. Value with a large real part and zero imaginary part returned.
`sinh(zz):`	
`C_SINH_RE`	| zz.re | too large. Value with correct angle and huge magnitude returned.
`C_SINH_IM`	| zz.im | too large. Complex(0,0) returned.

Footnotes

1. Such a function is called a constructor. A constructor for a type always has the same name as the type itself.

2 The Task Library

Introduction

Roadmap for the C++ Task Library Documentation

The three sections of this chapter describe the C++ Language System coroutine or task library.

- The first section, "A Set of C++ Classes for Co-routine Style Programming," written by Bjarne Stroustrup and revised and updated by Jonathan Shopiro, describes how the task library can be used. Read this section to learn about the basic use of the task library.
- The second section, "Extending the C++ Task System for Real-Time Control," by Jonathan Shopiro, describes new features of the task library to enable tasks to receive UNIX system signals.
- The task system internals for Release 3.0 are described in the third section, "A Porting Guide for the C++ Coroutine Library," by Stacey Keenan. This part tells you about the internals of the task library.
- The manual pages for the task library can be found at the end of this book.

A Set of C++ Classes for Co-routine Style Programming

NOTE This section is taken directly from a paper by Bjarne Stroustrup and Jonathan E. Shopiro.

Abstract

Some programs are most naturally expressed as a set of relatively independent activities communicating to achieve a common goal. Each activity, here called a *task*, has its own locus of control, a program to execute, and its own private data. Tasks can communicate by explicit sharing of data, by messages, or by data pipes.

This paper describes C++ classes for a range of styles of multi-programming techniques in a single language, single address-space environment. Each task is an instance of a user-defined class derived from class `task`, and the program of the task is the constructor of its class. A task can be suspended and resumed without interfering with its internal state. Class `qhead` and class `qtail` enable a wide range of message passing and data buffering schemes to be implemented simply.

The task system can be used for writing event driven simulations. Tasks execute in a simulated time frame presented by the variable `clock`, and objects of class `timer` provide a convenient and efficient facility for using the clock.

The implementation and use of these concepts rely heavily on the idea of derived classes. Familiarity with the C++ language would be an advantage for the reader.

Introduction

Some programs are most naturally expressed as a set of relatively independent activities communicating to achieve a common goal. Such activities, here called *tasks*, must be able to execute in parallel with each other and communicate through means convenient to the chosen style of task usage.

Facilities for multi-thread computation can be provided in the semantics of a language, as is done in Concurrent Pascal and Mesa or a language without such facilities can be augmented using special run-time support systems and library functions, as has been done for BCPL and C. The use of C classes to implement tasks represents an intermediate approach pioneered by Simula67.

The tools presented here[1] provide the basic facilities for several styles of multi-thread programming in a single language, single address-space environment. The underlying facility is a simple and efficient tasking system with non-preemptive scheduling. That is, a task will only be suspended on its own request, so no "system policy" can be enforced without the cooperation of all tasks. In contrast to pure co-routine systems, however, the task system provides a framework for processor sharing and communication between tasks. The task system is intended for applications, like event driven simulations, where tasks are used to express a quasi-parallel structure for a single program. For this class of applications a concept of simulated time is implemented. A unit of simulated time can represent any amount of real time, and it is possible to compute without consuming simulated time. A few simple random number generating classes and a histogram class for data gathering are also provided. The task system is not intended for handling real parallelism of some underlying real-time system. Consequently, no facilities are provided to map interrupts and other real-time events into the concepts provided by the task system.

The current version of the task library has a new degree of extensibility, so that it is now possible to write a class that represents an interrupt or signal that can be waited for.

Implementations of the task system have been used for about eight years on the UNIX system and other operating systems on 3B2, 3B20, VAX, and Motorola 680x0 hardware.

In the following sections the task library will be described in some detail, and examples of its use will be given. The classes used in the task system are presented. This allows a detailed and specific discussion of the concepts involved, but it unfortunately also implies that some concepts cannot be explained in detail where they are first mentioned.

Tasks

The publicly accessible functions and data of class `task` look like this:[2]

```
class task : public sched
{
public:
                task(char* name=0, int mode=0, int stacksize=0);
                ~task();
        task*   t_next;
        char*   t_name;
        int     waitvec(object**);
        int     waitlist(object* ...);
        void    wait(object*);
        void    delay(long);
        long    preempt();
        void    sleep(object* t =0);
        void    resultis(int);
        void    cancel(int);
};
```

The base class, `sched`, is responsible for scheduling and for the functionality that is common to tasks and timers (described below). The public part of its declaration is:

```
class sched : public object {
public:
                        sched();
            void        setclock(long);
            long        rdtime();
            int         rdstate();
            int         pending();
            void        cancel(int);
            int         result();
};
```

Class `sched` is used strictly as a base class: that is, only instances of derived classes are created.

A task is a locus of control, a virtual processor. It too can only be used as a base class, with the further limitation that only one level of derivation from class `task` is allowed

NOTE Multi-level derivation from class `task` is disallowed for implementation reasons. See the manual page for a workaround for this limitation.

A task executes the program supplied as the constructor of the derived class.[3] The most basic feature of a task is that it can be suspended and later resumed so that several tasks can run in quasi-parallel. Most member functions of class `task` are conditional or unconditional requests for suspension.

A task can be in one of three states:

RUNNING	The task is executing instructions or it will be scheduled to do so without further intervention from other tasks.
IDLE	The task is not in the RUNNING state, but it can be transferred to the RUNNING state by some suitable action. That is, it is waiting.
TERMINATED	The task has completed its work. It cannot be resumed, but its result can be retrieved.

The function `sched::rdstate()` returns the state.

A simple example of the use of tasks is where one task creates another to run in parallel with itself. Later the creator can obtain the result produced by the "secondary" task. For example, a task which counts the number of spaces in a string could be declared. First a class `Spaces` must be declared.

```
class Spaces : public task
{
public:
                        Spaces(char*);
};
```

In the case of class `Spaces` the declaration is trivial. It states that `Spaces` is derived from class `task` so that each object of class `Spaces` becomes an independently scheduled entity. The program for the task is provided by its constructor.

```
Spaces::Spaces(register char* s)
{
        register int    i = 0;
        register char   c;
        while (c = *s++)
                if (c == ' ') i++;
        resultis(i);
}
```

This function counts the spaces in its argument string and returns the result using the class `task` function `resultis()`. A task of class `Spaces` can now be created and used like this:

```
main()
{
        Spaces ss("a line with four spaces");
        int count = ss.result();
        printf("count = %d0, count);
        thistask->resultis(0);
}
```

When an object of class `Spaces` is created, like `ss` here, its constructor becomes a new task that runs in parallel with the task[4] that created it. A task can "return" an integer[5] value using the function `task::resultis(int)`. The task then becomes `TERMINATED` and the value is available for examination by the function `sched::result()`. That is, in this example `ss` will call `resultis()` with the argument `4`, which will be returned from `sched::result()` to the parent task. If a task calls `result()` for another task which has not yet completed the calling task will be suspended. After the other task finishes the call to `result()` in the waiting task will return. A task waiting for another to complete is `IDLE`. If a task calls `result()` for itself it will cause a run time error.[6]

A task cannot return a value using the usual function return mechanism; it must use `resultis()`. This function puts the task into the `TERMINATED` state from which it cannot be resumed.

Queues

A *queue* is a type of storage that is organized so that objects are retrieved from it in the order in which they were inserted into it. A queue has a *head* from which data is retrieved and a *tail* where data is inserted. With a little elaboration this basic type of data structure makes an excellent inter-task communication facility.

There is no "class queue" available to a user. Instead, the two classes `qhead` and `qtail` provide the services needed. There is a function `qtail::put()` which adds an object to the *tail* of a queue and a function `qhead::get()` which retrieves an object from the *head* of a queue. This allows explicit separation between the source and the recipient of data. The public part of the declaration of class qhead looks like this:

```
class qhead : public object
{
public:
                    qhead(int =WMODE, int =10000);
                    ~qhead();
          object*   get();
          int       putback(object*);
          int       rdcount();
          int       rdmode();
          int       rdmax();
          void      setmode(int);
          void      setmax(int);
          qtail*    tail();
          qhead*    cut();
          void      splice(qtail *);
          int       pending();
          void      print(int, int =0);
};
```

A queue can be created like this:

```
          qhead        qh;
```

To obtain a qtail for an existing queue execute tail() for its head:

```
          qtail*       qtp = qh.tail();
```

The queue could now be used as a one way inter-task communication channel by giving its head and tail as arguments to two new tasks, Producer and Consumer:

```
          Producer   pp(qtp);
          Consumer   cc(&qh);
```

The producer task pp can now put() objects to the tail of the queue (denoted by the pointer qtp) and the consumer task cc can get() those objects from its head (denoted by the pointer &qh). The function qtail::put() takes a pointer to a class object as argument, and qhead::get() returns such a pointer. Unless the user has specified otherwise a task executing qhead::get() will be suspended temporarily if the queue is empty.[7] After another task executes put() on the associated queue tail the suspended task will be resumed. Similarly a task executing qtail::put() on a full[8] queue will be suspended until some other task removes data from the queue.

The objects transmitted through a queue must be of class object or of some class derived from it. Class object (described under "The object Class") is provided by the task system, and it is up to the programmer to define types of objects suitable for each application.

In the current version of the task library `qhead` and `qtail` have the form of user extensions, but in the original version they were built in. Since extensibility was limited, the supplied classes had to support a wide range of programming styles. Thus they may seem "feature-rich." The new organization makes it easy to provide new kinds of queues and other forms of task interaction.

A Server Example

As an example of the use of tasks and queues we will define a *server* task that receives requests for service in the form of messages on a queue, handles the requests and returns replies on other queues. One could define a class `Message` as follows:

```
class Message : public object
{
public:
        int       r_operation;
        int       r_arg1;
        int       r_arg2;
        qtail*    r_reply;
};
```

A message, that is an object of class `Message`, describes an operation `r_operation` that is to be performed by the recipient of the message. Arguments for this operation can be passed as `r_arg1` and `r_arg2`, and the result of the operation is to be returned as a message on the queue denoted by `r_reply`.

A server for these messages can be defined as follows:

```
class Server : public task
{
public:
                  Server(qhead *);
};


Server::Server(qhead* in)
{
         for (;;) {
                  Message*   req = (Message *) in->get();
                  qtail*     reply = req->r_reply;
                  int        res = VALUE;
                  int        val;
                  switch (req->r_operation) {
                  case PLUS:
                  val = req->r_arg1 + req->r_arg2;
                  break;
                  case MINUS:
                  ...
                  default:
                  res = ERROR;
                  }
                  req->r_operation = res;
                req->r_arg1 = val;
                reply->put(req);
        }
}
```

This style of server has proved useful in many contexts. In particular, it is the backbone of many "message-based systems." In this particular example a server, that is an object of class `Server`, and the queue on which it depends can be declared:

```
qtail*    rq = new qtail;
Server*   ser = new Server(rq->head());
```

Other tasks can now send a request to this particular server through `rq`. For example:

```
qhead       rply;
qtail*      rply_to = rply.tail();
Message*    mess = new Message;


mess->r_operation = PLUS;
mess->r_arg1 = 1;
mess->r_arg2 = 2;
mess->r_reply = rply_to;


rq->put(mess);
mess = (Message *) rply.get();
if (mess->r_operation == ERROR) error();
```

More about Queues: Mode and Size

A queue head has a *mode* that controls what happens when `get()` is executed on an empty queue. In `EMODE` this causes a run time error. In `ZMODE` it will cause `get()` to return the `NULL` pointer instead of a pointer to an object. In `WMODE` a task executing a `get()` on an empty queue will wait on that queue until the queue becomes non-empty. Unless the user specifies the mode explicitly a queue head will be in `WMODE`. The function `qhead::rdmode()` returns the current mode and `qhead::setmode()` can be used to change it.

As mentioned above a queue also has a maximum size. This can be changed using `qhead::setmax()`, and read using `qhead::rdmax()`.

The mode and maximum size for a queue can also be specified when the queue is created. For example:

```
qhead    Q1(ZMODE, 10);
qhead*   QP2 = new qhead(EMODE, 64*BUFSIZE);
```

The public part of the declaration of class `qtail` is similar to that of class `qhead`. The two classes complement each other, and together they provide a representation of the general idea of a queue:

```
class qtail : public object
{
        // ...
public:
                 qtail(int = WMODE, int = 10000);
                 ~qtail();
         int     put(object*);
         int     rdspace();
         int     rdmax();
         int     rdmode();
         qtail*  cut();
         void    splice(qhead*);
         qhead*  head();
         void    setmode(int m);
         void    setmax(int m);
         int     pending();
         void    print(int, int =0);
};
```

A queue tail's mode controls what happens on queue overflow in the same way as a queue head's mode controls what happens on queue underflow. For example, when a task executes `put()` on a full queue where the queue tail is in `WMODE`, then that task will be suspended until the queue is no longer full. The modes of a queue's head and tail need not be the same.

Similarly the maximum number of objects which can be on a queue can be examined by `rdmax()` and changed by `setmax()`. Decreasing the maximum below the current number of objects on the queue is legal. Doing this simply implies that no new objects can be put on the queue until the queue has been drained below the new limit.

`qhead::rdcount()` returns the current number of objects in a queue, and `qtail::rdspace()` returns the number of objects which can be inserted into a queue before it becomes full.

`qhead::putback()` puts its argument back at the head of the queue, that is

```
qhead      qh(WMODE,10);
object*    oo = qh.get();
qh.putback(oo);
oo = qh.get();
```

will assign the same object to `oo` twice. `putback()` has proved to be a useful function in many systems in the past, and it also allows a queue head to operate as a stack. When `putback()` is used, the task executing it competes for queue space with tasks using `put()` on the queue's tail. A `putback()` to a full queue causes a run time error in both `EMODE` and `WMODE`. In `ZMODE` it returns `NULL`.

More about Tasks

When a task is created it can be given three arguments. The first is a character string pointer which is used to initialize the class `task` variable `t_name`. This name can be used to provide more readable output and does not affect the behavior of the task. The string denoted by the pointer will not be copied. The `t_name` is used by the debugging aids and error reporting functions described below. The other two class `task` arguments are tuning parameters and will be described below. If an argument is `NULL` a system default will be used. For example, we could have given each `Server` task a name like this:

```
class Server : public task
{
                Server(char*, qhead *);
};


void Server::Server(char* name, qhead* in)
: (name)  // argument for Server's base class task
{
        // ...
}


Server my_name_is_fred("fred", qhp);
```

`task::sleep(object* =0)` suspends the task unconditionally without specifying what is supposed to cause it to be resumed.

If an argument is given to `task::sleep(object* =0)` which is a pointer to a pending object, the task will be *remembered* by the object, so that after it is no longer pending, the task will be resumed.

`task::cancel()` puts a task into the TERMINATED state and sets the return value just like `resultis()`. However, `cancel()` does not invoke the scheduler so that one task can terminate another without losing control itself.

The pointer

```
                task*   thistask;
```

denotes the currently active task. If no tasks have been created its value is `0`. It is illegal to assign to `thistask`. The use of `thistask` enables the class `task` functions to be used from external functions without explicit passing of the current task's `this` pointer.

The pointer[9]

```
                task*   task_chain;
```

is the start of a chain of all tasks. In the following loop `t` points to every task in turn:

```
                task*   t;
                for (t=task_chain; t; t=t->t_next) ;
```

It is not possible to have only one task. Therefore, when the first task is created in a program another task is implicitly created. Its name is `main` and its code is the original `main()` function. It can be suspended and resumed like any other task. Please remember that a return from `main()` terminates a C program. If the "main" task should be terminated when there are other tasks which should be left running, then `resultis()` can be used. For example,

```
        thistask->resultis(0);
```

can be executed in `main()`. The program will then run on until no more tasks are or can become RUNNING.

It is illegal for a task to return. Always call `resultis()` instead of `return`, and never just "drop out of the bottom" of a task. Unless a task contains an infinite loop so that it will never terminate place a call of `resultis()` at the end of its body.

The task system does not provide a garbage collector. It is left to the programmer to ensure that pointers to deallocated store are not used.

Waiting

Functions like `sched::result()`, `qhead::get()`, and `qtail::put()` each provide a way of waiting for one single specific event to happen. More general facilities are sometimes needed.

When an object must be waited for, we say it is *pending*. For example,

- A queue head whose associated queue is empty is pending because if a task calls `get()` for it, the task must wait until some other task puts some data in the queue,
- Similarly, a queue tail whose queue is full is pending because a `put()` must wait, and

- A task that has not terminated is pending because its result is not available.

  Each class derived from object may have its own definition of the virtual `pending()` function. An object may have several operations that could suspend the calling task, but it can have only one definition of `pending()`. Therefore (for example) it is not possible to combine a queue head and a queue tail into a single object, because the former is pending when its queue is empty, and the latter when its queue is full. New kinds of objects, with new kinds of interaction can be added to the task library, with the fundamental requirement being a definition of `pending()` for the new datatype.

`task::wait(object*)` provides a way of waiting on an arbitrary object. If the argument points to a pending object, the calling task will be suspended until the object is no longer pending. If the argument is not pending the caller will not be suspended at all. For example, if `taskp` is a pointer to a task then

```
        wait(taskp);
```

will suspend the task executing it until the task denoted by `taskp` finishes.

Each class derived from class `object` which is ever going to be "waited on" must have rules specifying under which conditions a task executing a `wait()` for it will be resumed. The rules for class `task`, `qhead`, and `qtail` have been stated.

The conditions for wakeup are reflected in state changes in the objects, and are not just transitory unrecorded signals. For example, if a task executes a `wait()` for a non-empty `qhead` it will immediately continue, that is the condition for returning from a `wait()` for a `qhead` is that the queue is non-empty, not a brief state change from empty to non-empty. Rules of this type simplify programming considerably by eliminating race conditions.

> When the state of an object changes from pending to not pending, `object::alert()` must be called for the object. This function changes the state of all tasks "remembered" by the object from `IDLE` to `RUNNING` and puts them on the scheduler's `run_chain`. Thus all such operations should be member functions of the object's class or a related class. For example, in `qtail::put()`, if the queue was empty, a call to `alert()` is made for the associated queue head. If it was possible to put an object on a queue without calling a member function, then there would be no guarantee that `alert()` would be called.

The functions `task::waitvec()` and `task::waitlist()` suspend a task waiting for one of a list of objects, for example to wait for messages to arrive on one of a number of queue heads. `waitlist(object* ...)` 10 takes a list of object pointers terminated by a zero as argument; for example:

```
        qhead*   q1;
        qhead*   q2;
        // ...
        short    who = waitlist(q1, q2, 0);
```

will suspend the task executing it until either `q1` or `q2` is non-empty. If either is non-empty when `waitlist()` is called the task will continue immediately.

The value returned is the position in the list of the object that caused the return from the wait, that is if q2 caused the task to resume the value 1 will be assigned to who. Positions are numbered starting from *0*. `waitlist()` can take any number of arguments. The degenerate example

```
waitlist(0);
```

causes unconditional suspension of the task executing it without any guarantee of later resumption. It is equivalent to `sleep()` and `wait(0)`.

Please note that one should not assume that because `waitlist()` returns a particular value indicating one object as the cause of resumption none of the other objects are "ready." The value returned by `waitlist()` only indicates what is known to have happened, and it does not exclude other independent possibilities.

> However if `waitlist()` indicates a particular object, that object is guaranteed to be "ready," because `waitlist()` does not return until the object is no longer pending.

Because every class in the task system allows non-blocking examination of the conditions which might lead to suspension using the three wait functions, the value returned by `waitlist()` can always be ignored. The information it conveys can always be obtained by direct inquiry. In many cases, however, the value returned can be trusted and used to write simpler, more efficient programs.

`waitvec()`, a variation of `waitlist()`. takes the address of a vector holding a list of object pointers. For example:

```
object*   vec[] = { q1, q2, 0 };
short     who = waitvec(vec);
```

is equivalent to the previous example.

System Time and Timers

The `long` variable `clock` measures simulated time. It is initialized to zero. It is illegal to assign to `clock`.

`task::delay(long)` suspends a task for a specified time. That is,

```
long   t = clock;
delay(n);
actual_delay = clock-t;
```

will assign the value `n` to `actual_delay`. `delay()` is useful for representing service delays in simulations. While a task is delayed in this way its state is still RUNNING, but it will not be affected by the actions of other tasks except if `cancel()` or `preempt()` is used on it. `delay(n)` makes an `IDLE` task RUNNING so that it will start executing at time `clock+n`.

`task::preempt()` makes a RUNNING task `IDLE` and returns the number of time units left of its delay. Applying `preempt()` to an `IDLE` or TERMINATED task causes a run time error. This function is useful when tasks are used to represent processes in a system with preemptive scheduling and delay times are used to represent the time used by executing processes. The value returned by `preempt()` allows the preempted task to be re-started with a new delay time which is a function of the delay time at the time of preemption.

For example:

```
                long   time_left = other_task->preempt();
                // ...
                other_task->delay(time_left+10);
```

A `timer` provides a facility for implementing time-outs and other time dependent phenomena.

Class `timer` has this declaration:

```
        class timer : public sched {
        public:
                       timer(long);
                       ~timer();
                void   reset(long);
                void   print(int, int =0);
        };
```

A timer is quite similar to a task with a constructor consisting of the single statement

```
                delay(d);
```

that is, when a timer is created it simply waits for the number of time units given to it as its argument, and then wakes up any tasks waiting for it.

A timer's state can be either `RUNNING` or `TERMINATED`. This state can be inspected by using `sched::rdstate()`.

A common use of timers is to wait for a task and a timer. For example, one can wait for the completion of a task handling a simulated input operation and also on a timer. The timer ensures that the waiting task will eventually be resumed even if the input operation is never completed:[11]

```
                timer*   tt = new timer(15);
                short    res = waitlist(io_ptr,tt,0);
                switch (res) {
                case 0:
                         /* normal completion of i/o */
                         ...
                         break;
                case 1:
                         /* time out occurred */
                         ...
                         break;
                default:
                         error(IMPOSSIBLE);
                }
```

sched::result and sched::cancel() have the same use and effects on timers as on tasks. Since there is no timer::resultis(), the value returned by sched::result() is undefined for a timer unless cancel() was used.

timer::reset() re-sets the timer delay to the value of its argument. This makes repeated use of timers possible. A timer can be reset() even when it is TERMINATED.

A unit of simulated time can be used to represent any unit of real time. Only delay() causes the clock to advance.

More About Queues: Cutting and Splicing

One of the most convenient and powerful ways of using tasks involves tasks defined to do a transformation on a data stream. Such a task is called a filter. It reads its input from one queue and writes its output onto another queue. Tasks at the "other ends" of these queues tend to view these queues plus the filter as one entity. The data source simply sees an output queue that is being emptied at some rate, and the task at the receiving end sees an input queue being filled. In other words, a task sees only its input and output queues and cares little about the "internal organization" of the programs that operate on the other ends of those queues.

For example, one task could produce a stream of lines of characters, that is objects of class Line, and another expect an input stream consisting of words, that is objects of class Word. A filter that handles the conversion could be defined and used like this:

```
class Line_to_word : task
{
public:
                Line_to_word(qhead*, qtail*);
        Word*   next_word(Line*);
};


Line_to_word::Line_to_word(qhead* in_q, qtail* out_q)
{
        Line*   l;
        Word*   w;
        for(;;) {
                l = (Line *) in_q->get();
                while(w = next_word(l)) out_q->put((object *)w);
        }
}
```

```
qhead*          line_q = new qhead(WMODE,10);
qtail*          word_q = new qtail(WMODE,50);
Producer*       prod = new Producer(line_q->tail());
Consumer*       cons = new Consumer(word_q->head());
Line_to_word*   filt = new Line_to_word(line_q, word_q);
```

In this way the filter `filt` is programmed into the path between `cons` and `prod` using two queues to separate `filt`'s input from its output.

This is a fairly static use of a filter. Often one would like to insert a filter into an existing data path. For example, a macro-based text formatting program could be organized as a sequence of filters — each doing its small part of the common task. First some filters re-arrange the input into a form suitable for the formatter proper, then the "input independent" formatter does its job producing output of a standard form, and last some output filters adjust this output to a form suitable for physical output. The task `filt` is an example of such a filter. In this scenario it would be useful to have each macro defined as a filter which the formatter proper inserts just in front of itself when the macro expansion is needed and which removes itself when it is not needed any more. Assuming that data streams are represented by queues, this can be achieved by using the class `qhead` functions `cut()` and `splice()`.

When the task `formatter` recognizes a call to the macro `foo` it creates a new task of class `Macro` to handle a macro of type `FOO` and diverts its own input through it. This is done by first "cutting" the input queue to create a place to insert the new filter, and then creating the filter giving it the new `qhead` and `qtail` as arguments:

```
qhead*   newhead = input_queue->cut();
qtail*   newtail = input_queue->tail();
Macro*   f = new Macro(FOO,newhead,newtail);
```

`qhead::cut()` splits the queue to which it is applied into two. `newhead`, the pointer returned from `cut()`, denotes the `qhead` for the original queue and has the same `mode` as the original `qhead`. The original `qhead` is now attached to a new empty queue with the same `max` as the original.

Puts to the original `qtail` will therefore place objects on the filter's input queue, and gets from the original `qhead` will retrieve objects from the filter's output queue.

The result of these operations has been to insert a filter with an input and an output queue into a queue without changing the appearance of that queue to anyone using it, and without halting the flow of objects through that queue. In our example the macro expansion filter `foo` will `get()` the input which would otherwise have gone to the formatter, interpret it as macro arguments, and output the expanded input as its output.

The filter can be removed again by splicing its input and output queues together with `qhead::splice()`:

```
newhead->splice(newtail);
```

`splice()` deletes the `qhead` to which it is applied, the `qtail` given to it as an argument, and the queue denoted by that `qtail`. If the `splice()` operation causes an empty queue to become non-empty or a full queue to become non-full all tasks waiting for such a state change are resumed.

Deleting the filter completes the cleanup:

```
delete f;
```

Typically a filter would remove itself when its task was completed, because the task that inserted it would not be programmed to be aware of the presence of the filter it inserted. The sequence of operations which enables a task to remove itself without a trace is:

```
cancel(any_value);
delete this;
```

This will work because `cancel()` does not imply immediate suspension, only a guarantee that the task cannot be resumed.

`qtail::cut()` and `qtail::splice()` are similar to `qhead`, but they operate on the other end of the queue.

Encapsulation

Passing information between tasks through queues can lead to rather tedious, repetitive (and therefore error prone) packing and unpacking of information into messages. Simple encapsulation techniques can be used to relieve the programmer of this. For example, by adding a constructor to the class `Message` the server example could be re-written thus:

```
class Message : object
{
public:
        int       r_operation;
        int       r_arg1;
        int       r_arg2;
        qtail*    r_reply;
                  Message(int op, int a1, int a2, qtail* rp) :
                  r_operation(op), r_arg1(a1),
                  r_arg2(a2), r_reply(rp) {}
};

        Message*   mess;
        rq->put(new Message(PLUS, 1, 2, rply_to));
        mess = (Message *) rply.get();
        if (mess->r_operation == ERROR) error();
```

Furthermore, because the message queues obviously are meant to hold only `Message` objects a specific message queue could be defined and used:

```
class Mqhead : qhead
{
public:
       Message*   get() { return (Message *) qhead::get(); };
};


class Mqtail : qtail
{
public:
       int    put(Message* m) { return qtail::put(m); };
};
```

The use of `Mqtail::put()` ensures that only class `Message` objects are put on the queue, and no type cast is needed when class `Message` objects are taken from the queue using `Mqhead.get()`. For example:

```
        mess = rply->get();
```

Because the body of `Mqtail::put()` is present in the class `Mqtail`, declaration calls of `Mqtail::put()` will be expanded inline. This ensures that using a `Mqtail` is no less efficient than using a `qtail` directly. In many cases some error handling can also be handled by the derived `put()` and `get()` functions.

An alternative solution is to provide the server class with functions which handle the packing:

```
class Server : task
{
        qtail*   inp;
public:
                 Server(char*, qhead*);
        int      plus(int, int, Mqtail *);
        int      minus(int, int, Mqtail *);
};


int Server::plus(int arg1, int arg2, Mqtail * rqt)
{
        Message*   mess;
        int        x;
        inp->put(new Message(PLUS,arg1,arg2,rqt));
        mess = rqt->head()->get();
        x = mess->r_operation;
        delete mess;
        return x;
}
```

so now the server task can be requested to perform services like this:

```
        Mqtail   qq;
        Server   ss("plus_and_minus", 0, 0);
        int      two = ss.plus(1, 1, &qq);
        int      ten = ss.minus(12, 2, &qq);
```

For large programs this style of inter-task communication promises not only increased clarity, but also increased efficiency. The message queue interaction may, where necessary, be transparently replaced by a specially tailored inter-task communication facility.

These techniques are now widely applied in C++ programming, but when this paper was first written, they were new to C.

Histograms and Random Numbers

To ease data gathering class histogram is provided.

```
struct histogram
// "nbin" bins covering the range [l:r] uniformly
// nbin*binsize == r-l
{
        int     l, r;
        int     binsize;
        int     nbin;
        int*    h;
        long    sum;
        long    sqsum;
                histogram(int=16, int=0, int=16);
        void    add(int);
        void    print();
};
```

A histogram consists of `nbin` bins `h[0], ... h[nbin-1]` covering a range `[l:r]` of integers. The function `add()` adds one to the correct bin for its integer argument. The sum of the integers added is maintained in `sum`, and the sum of their squares is maintained in `sqsum`. If an argument to `add()` is outside the range `[l:r]` the range is adapted by either decreasing `l` or increasing `r`. The number of bins remains constant so the size of the range covered by a bin is doubled each time the size of the range `[l:r]` is. The `print()` function prints out the numbers of entries for each non-empty bin.

In most simulations some form of random number generation is needed. The generators provided here are intended to help the developer of a simulation to get started and to provide a paradigm for generators of more suitable distributions.

```
class randint
// uniform distribution in the interval [0,MAXINT_AS_FLOAT]
{
        long    randx;
public:
                randint(long s = 0);
        void    seed(long s);
        int     draw();
        float   fdraw();
};
```

The following program shows the use of class `randint`. The `ints` returned by `randint::draw()` are uniformly distributed in the interval `[0:largest_positive_int]`. The `floats` returned by `randint::fdraw()` are uniformly distributed in the interval `[0:1]`.

```
main()
{
        randint    ir;
        register   i;
        for (i=0; i<100; i++)
                printf("i=%d f=%f ", ir.draw(), ir.fdraw());
}
```

Each object of class `randint` provides an independent sequence of random numbers. `randint::seed()` can be used to reinitialize a generator. The `draw()` function calls the underlying C library `rand(3)`. Using class `randint`, generators for other distributions are easily programmed. Note that `erand::draw()` calls `log()` from the math library, so a program using it must be loaded with `-lm`.

```
class urand : public randint
// uniform distribution in the interval [low,high]
{
public:
        int   low, high;
              urand(int l, int h) { low=l; high=h; }
        int   draw() { return int(low + (high-low) *
                 (0+randint::draw()/MAXINT_AS_FLOAT)); }
};


class erand : public randint
// exponential distribution random number generator
{
public:
        int   mean;
              erand(int m) { mean=m; };
        int   draw();
};
```

Implementation Details

The following sections contain many implementation-dependent details. The implementation described is the UNIX version. Implementation-dependent information is unfortunately often necessary to allow tuning and ease debugging.

Task Stack Allocation

The two arguments `mode` and `stacksize` allow the user to guide the system's handling of the task. Their exact interpretation is implementation dependent. Users who are not interested in implementation details and/or want a more portable program should set them both to zero. The system will then choose (hopefully reasonable) implementation-dependent default values.

The `stacksize` argument indicates the maximum amount of stack storage that the task is allowed to use. Using more is an error. It will be expressed in a unit of store (typically machine words) suitable for stack allocation on the host system.

The mode provides additional information. The value `SHARED` indicates that the stack space should be taken from the stack space of the parent task, that is the task which created the new task. Where `SHARED` stacks are used the active part of the stack is copied to a save area when a task is suspended, and copied back when it is resumed. *Since* `SHARED` *stack locations are not dedicated to a single task pointers to local variables should not be passed to other tasks.* The time needed to suspend and resume a task with `SHARED` stack is approximately proportional to the amount of stack space actually used at the time of suspension.

If, on the other hand, the mode is `DEDICATED` then a new and separate stack area is allocated, and no copying of stack space will occur.

Scheduling

Functions of a system class, known as the scheduler, are invoked as the result of any function of class `task` which causes the suspension of a running task, and may be invoked by any function from the standard classes described here. The scheduler selects the next task to run. When the scheduler finds no more tasks to run, and there are no `interrupt_handlers`, it examines the pointer variable `exit_fct`, and if this is non-zero the scheduler will call the function denoted by it.

Whenever `clock` is advanced the scheduler examines the pointer variable `clock_task`. If this denotes a task, then that task will be resumed before any other task. The `clock_task` must be `IDLE` when resumed by the scheduler. The class `task` function `sleep()` is useful to ensure this.

Debugging and Tuning Aids

The task system has been designed under the assumption that a typical use of tasks may involve hundreds of tasks and need tuning to achieve an acceptable time-space tradeoff. The task of debugging such a system can safely be assumed to be non-trivial.

Classes were used in the implementation of the task system largely because they allow the scope of data and functions to be explicitly restricted to the object to which they belong. This allows better type checking of a multi-threaded program than could be achieved by a function-based implementation. The classes which constitute the task system were designed to allow quite strong type checking of programs using them.

A number of run time errors are detected by the task system. For example it is illegal to `delete` a queue on which a task is waiting. When such a run time error is detected the task system function `object::task_error` is called with the number of the error and the `this` pointer of the object which caused the error as arguments. A list of run time errors appears under "Run-Time Errors." `task_error()`

will in turn examine the pointer `error_fct`, and if this is non-zero call the function denoted by it with a copy of its own arguments. function Otherwise `task_error()` will call the system function `exit()` with the error number as argument.

When returning from `task_error()` after executing an `error_fct` which returned rather than using `exit()` the task system will re-try the operation which caused the error (provided that `error_fct` could have affected the condition which caused the error). For example, a `put()` to a `qhead` will be re-tried because the user's `error_fct` might have either caused the `get()` function to be used on the queue, or used `chmax()` to allow more objects to be inserted into that queue.

> This error handling mechanism is primarily designed for debugging and it is expected that user error functions will print some appropriate error message and exit.

Beware of infinite loops.

All task system classes have a function `print()` which can be used to print the contents of their objects on `stdout`. A `print()` function takes an `int` argument indicating the amount of information to be printed. `print(0)` gives the minimum amount of information, `print(VERBOSE)` rather more, and `print(CHAIN)` will call `print()` for objects on lists associated with the object with its own arguments. The `print()` argument constants can be combined by the `or` operator. For example

```
thistask->print(VERBOSE);
run_chain->print(VERBOSE|CHAIN);
```

will verbosely describe every non-`TERMINATED` timer and every `RUNNING` task. For tasks information about the run time stack is printed by `print(STACK)`. If the variable `_hwm` is set to a non-zero value, `print(STACK)` will also give an estimate of the maximum amount of stack space ever used by the task, the stack's "high water mark." For tasks that share a stack, the high water mark printed will be the high water mark of the most greedy task. For example, information describing stack usage for all tasks can be printed by:

```
task_chain->print(STACK|CHAIN);
```

The output of the `print()` functions is implementation-dependent and hopefully self-explanatory.

Overheads and Performance

The store used for representing a class object in addition to the user specified data is:

object	3 words
timer	5 words
task	18 words + stacksize
queue	15 words (including the qhead and the qtail)

The times needed to execute some of the task system functions are (very) approximately:

C procedure call + return	1 unit
task suspend + resume	9 units (using result())
put	2 units
get	2 units
wait, waitvec, or waitlist	3 units

The last four actions can all cause a task to be suspended. When this happens add 6 units of time.

For timing results relative to UNIX process switching, see "Extending the C++ Task System for Real-Time Control."

The task system uses about 15K bytes of store for program and data, but much of this is redundant virtual function tables that will be eliminated in a future version of the C++ compiler.

The `object` Class

The task system as described above is implemented using a lower level of abstraction based on the direct use of the class `object`. Class `object` can also be used as a base for other (user defined) abstractions, but beware, it is an implementation tool that is not intended to be used directly.

Class `object` is a base class for all classes in the task system and also the most basic facility for inter-task communication. The declaration of class `object` looks like this:

```
class object
{
friend sched;
friend task;
    olink*          o_link;
public:
    object*         o_next;
    virtual int     o_type();
                    object() { o_link=0; o_next=0; }
                    ~object();
    void            remember(task* t) { o_link = new olink(t,o_link); }
    void            forget(task*);     // remove all occurrences of task from chain
    void            alert();           // prepare IDLE tasks for scheduling
    virtual int     pending();         // TRUE if this object should be waited for
    virtual void    print(int, int =0);// first arg VERBOSE, CHAIN, or STACK
};
```

The task system implements objects of type `TASK`, `QHEAD`, `QTAIL`, and `TIMER`.

Virtual functions make it unnecessary to ever test the type of an object. The virtual function `o_type()` is never called.

A task can be added to the set of tasks "remembered" by an object by executing `object::remember()` and a task can be removed from this set by executing `object::forget()`. Executing `object::alert()` has the effect of transferring all `IDLE` tasks remembered by the object to the `run_chain` and the `RUNNING` state.

> The virtual function `object::pending()` provides the "glue" that allows new kinds of objects and new communication protocols to be added to the task system. The object may have any kind of operation that may cause the invoking task to wait, but it must implement its own version of `pending()` to tell whether the operation would cause a wait.

A task can be "remembered" by several objects or several times by the same object without any ill effects. `forget()` will insure that its argument is not "remembered" any more, and it causes no bad effects when used for an object that does not "remember" its argument task. No record is kept of how many `alert()` operations have been executed on an object. `alert()` does not cause an object to `forget()` tasks. Executing a `remember()` does not suspend a task. Applying `alert()` to an object that does not remember any tasks is legal, but has no effect. Caveat emptor!

The functions `object::remember()`, `object::forget()`, `object::pending()`, and `object::alert()` provide a simple, efficient, but unstructured and therefore error-prone communication mechanism.

The declarations for the task system classes can be found in `/usr/include/CC/task.h` on systems where it is implemented.

Run Time Errors

When an error is detected at run time, `task_error()` is called. This function will examine `error_fct` and if this variable denotes a function, that function will be called with the error number and `this` as arguments, otherwise the error number will be given as an argument to `print_error()` which will print an error message on `stderr` and terminate the program.

E_OLINK	Attempt to delete an object which remembers a task.
E_ONEXT	Attempt to delete an object which is still on some chain.
E_GETEMPTY	Attempt to get from an empty queue in E_MODE.
E_PUTOBJ	Attempt to put an object already on some queue.
E_PUTFULL	Attempt to put to a full queue in E_MODE.
E_BACKOBJ	Attempt to putback an object already on some queue.
E_BACKFULL	Attempt to putback to a full queue in E_MODE.
E_SETCLOCK	Clock was non-zero when `setclock()` was called.
E_CLOCKIDLE	The clock_task was not `IDLE` when the clock was advanced.
E_RESTERM	Attempt to resume a `TERMINATED` task.
E_RESRUN	Attempt to resume a `RUNNING` task.
E_NEGTIME	Negative argument to `delay()`.
E_RESOBJ	Attempt to resume task or timer already on some queue.
E_HISTO	Bad arguments for histogram constructor.
E_STACK	Task run time stack overflow.
E_STORE	No more free store — `new()` failed.
E_TASKMODE	Illegal mode argument for task constructor.

E_TASKDEL	Attempt to delete a non-TERMINATED task.
E_TASKPRE	Attempt to preempt a non-RUNNING task.
E_TIMERDEL	Attempt to delete a non-TERMINATED timer.
E_SCHTIME	Scheduler run chain is corrupted: bad time.
E_SCHOBJ	Sched object used directly instead of as a base class.
E_QDEL	Attempt to delete a non-empty queue.
E_RESULT	A task attempted to obtain its own `result()`.
E_WAIT	A task attempted to `wait()` for itself to TERMINATE.
E_FUNCS	Internal error — cannot determine the call frame layout.
E_FRAMES	Internal error — cannot determine frame size.
E_REGMASK	Internal error — unexpected register mask.
E_FUDGE_SIZE	Internal error — fudged frame too big.
E_NO_HNDLR	No handler for the generated signal.
E_BADSIG	Attempt to use a signal number that is out of range.
E_LOSTHNDLR	Signal handler not on chain.

A Program Using Tasks

```
#include <task.h>

/* trivial test example:
        make a set of tasks which pass an object round between themselves
        use printf to indicate progress
        WARNING: this program sets up an infinite loop
*/

class pc : task
{
                pc(char*, qtail*, qhead *);
};

pc::pc(char* n, qtail* t, qhead * h) : (n,0,0)
{
        printf("new pc(%s,%d,%d)\n",n,t,h);

        while (1) {
                object*   p = h->get();
                printf("task %s\n",n);
                t->put(p);
        }
}

main()
{
        qhead*   hh = new qhead;
        qtail*   t = hh->tail();
        qhead*   h;
        short    i;

        printf("main\n");

        for (i=0; i<20; i++) {
                 char*   n = new char[2]; /* make a one letter task name */
                 n[0] = 'a'+i;
                 n[1] = 0;

                 h = new qhead;
                 new pc(n,t,h);
                 printf("main()'s loop\n");
                 t = h->tail();
        }

        new pc("first pc",t,hh);
        printf("main: here we go\n");
        t->put(new object);
        printf("main: exit\n");
        thistask->resultis(0);
}
```

Extending the C++ Task System for Real-Time Control

NOTE This section is taken from a paper by Jonathan E. Shopiro.

Abstract

The task system for coroutine programming was one of the first libraries written in C++ and it has served admirably in several applications. It is small, efficient, and easy to use. As part of a robot control project, it was extended to support real-time control. The new task library is more robust, more easily extendible, and more portable than the original. It is upward compatible, so that programs written for the old task library can still be used. This section documents the new features and the internal structure of the revised system, and is intended for users of the task library and for authors of other coroutine systems.

Overview

The C++ task library is a coroutine[12] support system for C++. A task is an object with an associated coroutine. The task library includes a scheduler that enables each task to execute just when it has work to do, and to wait when necessary for whatever is needed.

Programming with tasks is particularly appropriate for simulations, real-time process control, and other applications which are naturally represented as sets of concurrent activities. A task can represent a simple part of a complex system, and when the task gains control, it can process its current input data, perhaps creating other data that will be processed by other tasks. It can then relinquish control, waiting for more input or an external event.

In a program using the C++ task system, all tasks share the same address space so that pointers can be passed between tasks, and it is easy to share common data structures. Also, the scheduler is non-preemptive, so that each task runs until it explicitly gives up the single processor, and only then does the scheduler choose a new task to run. This eliminates the need for locks on shared data (which would be required if preemptive scheduling or multiple processors were used) and allows task-switching to be accomplished with low overhead, but requires the programmer to be careful that no task monopolizes the processor.

The rest of this section is an overview of control flow in the task system along with a brief note on task system performance. The section "Real-Time Extensions" describes the interrupt handler class and how it can be used to provide real-time response to external events. Familiarity with C++ is assumed.

The Structure of the Task System

Control in the task system is based on a concept of operations which may succeed immediately or be blocked, and *objects*[13] which may be *ready* or *pending* (not ready). When a task executes a blocking operation on an object that is ready, the operation succeeds immediately and the task continues running, but if the object is pending, the task waits. Control then returns to the scheduler, which chooses the next task from the *run chain,* a list that contains all the tasks that are ready to run (not waiting or terminated). For example, a queue head is ready when the associated queue has data, and `get` (which extracts an item from the queue) is a blocking operation for queue heads. Similarly, `put` is a blocking operation for queue tails, which are ready unless the associated queue is full.

Each different kind of object can have its own way of determining whether it is ready or not, which makes it easy to add new capabilities to the system. On the other hand, each kind of object can have only one criterion for readiness (although it may have several blocking operations), so it is not possible for one object to act as both a queue head and a queue tail, for example.

Each object contains a list (the *remember chain*) of the tasks that are waiting for it. When any operation changes the state of a pending object so that it becomes ready, those tasks are moved to the run chain; this is called an *alert*. Thus the cycle is: a task runs until it blocks; it is saved on the remember chain of one or more pending objects; some other task or an interrupt alerts the object; the original task is moved to the run chain; eventually the task runs again.

Task System Performance

The fundamental operations of the task system are task creation and task switching. In order to make a meaningful evaluation of their performance, equivalent programs using tasks and UNIX Operating System processes were written. These programs are given under "Example Programs." Each of the first pair of programs (`tcreate.c` and `ucreate.c`) repeatedly creates new trivial tasks (processes) and waits for them to terminate. Each of the second pair of programs (`tswitch.c` and `uswitch.c`) creates a single child task (process) and repeatedly exchanges control with it through a pair of semaphores (see under "Semaphores") in the task version, and through UNIX signals in the process version. The programs were run on a SUN 3/280 under 4.2 BSD, using the free store allocator (`malloc.c`) from Ninth Edition UNIX, which is much faster than the one supplied with 4.2 BSD. The results were that `tcreate.c` was 37 times faster than `ucreate.c`, and `tswitch.c` was 10 times faster than `uswitch.c`.

It is important to note that the task system and the UNIX Operating System are not equivalent and that the results of these performance measurements do not imply that the task system is 23.5 times better than UNIX. Among the significant differences between tasks and processes are the following.

- A set of tasks runs as a single UNIX process. The task system relies on the UNIX Operating System for I/O, memory management, etc.
- Tasks share an address space, while processes have separate address spaces. This means that tasks can share data by simply passing pointers, while processes must go through one of several much more complex and expensive procedures to share data. By the same token, tasks can interfere with each other as easily as they can cooperate, while errant processes usually kill only themselves.
- The task system can support two or three orders of magnitude more concurrent tasks (especially with the SHARED option; see "Task Switching") than the UNIX Operating System can support processes. It is not uncommon for a simulation to require thousands of tasks.

The memory required for the task system is about 14,000 bytes for code and data, plus about 70 bytes per task, plus stack storage for each task. By default each task has its own stack buffer with a default size of 3000 bytes, but tasks can share a stack buffer and then storage is required only for the active stack of each task (typically 50 to 100 bytes). This option is very useful for applications with thousands of tasks. Queues occupy 60 bytes (including both head and tail) plus the size of whatever is stored on the queue. Lists of tasks are maintained in various places, for example the run chain and remember chains; each occurrence of a task on a list adds 8 bytes to the total memory requirement.

Real-Time Extensions

The application that motivated this work on the task system was a control system for two robots operating in the same workspace. The most important requirement of this application that was not fulfilled by the original task system was the need for tasks to wait for external events. For example, after a motion command was sent to a robot, the task that sent the command needed to wait for the interrupt that was generated by the robot hardware when the command was complete or had failed. A related requirement of some real time systems is to respond to external events in a timely manner, for example to retrieve data from an unbuffered external device. Also, in the original task system, the scheduler would exit when the run chain was empty. This is inappropriate in a system that is intended to respond to external events because some task might become runnable after an interrupt.

Hardware interrupts are handled differently by different machines and operating systems, so the interface to the task system must also vary. For didactic reasons, the version described here is for the UNIX Operating System using signals as interrupts, but it should be clear how to adapt it to other environments.

In the task system events that can be waited for are represented by instances of class `object` or derived classes. When the function `object::alert()` is called, the tasks that were waiting for that object are made runnable. A natural solution to the problem of waiting for external events was to define a new kind of object to represent external events, and when such an event occurs, to call `object::alert()` for the appropriate object. These objects are called interrupt handlers.

```
class Interrupt_handler : public object {
        int id;                 // signal or interrupt number
        int got_interrupt;      // an interrupt has been received but not alerted
        Interrupt_handler *old; // previous handler for this signal
        virtual void interrupt() {}// runs at real time
public:
        int pending();          // FALSE once after interrupt
        Interrupt_handler(int sig_num);
        ~Interrupt_handler();
};
```

After an interrupt handler is created, a task can wait for it, exactly as for any other object. When the interrupt occurs, the handler's `interrupt()` function will be executed immediately, or rather, as soon as the operating system can route the interrupt to the process. When the interrupt function returns, control will resume at the point where the current task was interrupted.

At the next entry to the scheduler, when the currently running task blocks, a special task, the *interrupt alerter,* will be scheduled. This task alerts the handler (and any other handlers that have received interrupts since it was last scheduled). Thus the waiting task becomes runnable. As long as any interrupt handler exists, the scheduler will wait for an interrupt, rather than exiting when the run chain is empty. The `pending` function for an interrupt handler always returns TRUE except the first time it is called after an interrupt occurs.

`Interrupt_handler::interrupt()` is a null function, but since it is virtual, the programmer can specify the action to be taken at interrupt time by simply defining an `interrupt()` function in a class derived from `Interrupt_handler`. An example is given under "Interrupts." In this way real-time response can be obtained without resorting to a preemptive, priority-based scheduler which would be more complex and less efficient, and would require locking of shared data structures.

Avoiding Interference

Whenever shared data structures are manipulated by concurrent processes, there is the potential for interference, where one process is in the middle of modifying a data structure and another process accesses it and finds it in an invalid state. Segments of code that access shared data structures are called *critical regions*.[14] If more than one process can be in a critical region at one time, there is a potential for interference.

Interference is easy to avoid in the task system, because of the non-preemptive nature of the scheduler. There are only two ways in which interference can arise: a task switch occurring within a critical region, or an interrupt routine that accesses shared data.

It is almost always possible to write code so that no operation that could cause a task to block is inside a critical region. The style of programming where coroutines share information by sending messages to each other in the form of objects on queues typically leads to programs where there are no shared data structures or critical regions at all. Even if coroutines must share access to a data structure and alternately modify it, no problems will arise if the routines that do the modification refrain from operations that could cause the task to block. A properly modular program will generally satisfy this requirement without any extra effort.

Semaphores

If, for some unusual reason, it is necessary to put an operation that could cause the task to block in a critical region, then the affected data structure should be protected by a semaphore, which will allow only one task at a time to access the object. The following example code outlines this technique.

```
class My_data {
        Semaphore     sema;
        // user data
public:
        void          lock() { sema.wait(); }
        void          unlock() { sema.signal(); }
                      My_data() : sema(1) { ... }  // see note
};
```

Each critical region must begin with a call to `My_data::lock()` for the object to be accessed, and end with a call to `My_data::unlock()`. This will ensure that no interference occurs, even if the operations in the critical region cause the task to block.[15]

The implementation of semaphores using the task system is easy.

```
class Semaphore : public object {
        int     sigs;  // the number of excess signals
public:
                Semaphore(int i =0) { sigs = i; }
        int     pending() { return sigs <= 0; }
        void    wait();
        void    signal() { if (sigs++ == 0) alert(); }
};


void
Semaphore::wait()
{
        for (;;) {
                if (--sigs >= 0)
                return;
                sigs++;
                thistask->sleep(this);
        }
}
```

Semaphores are useful tools for building other kinds of synchronization besides mutual exclusion. For example, whenever one task wants to wait for an operation to be completed by another task, it can wait on a semaphore.

Interrupts

The other case where interference can occur is a little more complex. The `interrupt()` routine of an `Interrupt_handler` can be executed at any time, and it would be contrary to the reason for its existence to lock it out. The mechanism that alerts the handler after the interrupt has occurred is carefully designed to be safe from interference, and sometimes the alert is all that is necessary for an application. If it is necessary to gather data from an external device immediately after an interrupt occurs, but the interrupts do not come in rapid succession (for example, the next interrupt won't occur until after the device is reset), the interrupt routine can save the data and the task that is waiting for the interrupt can process the data before resetting the device. In this case even though the data is shared, the interrupt routine cannot access the data at the same time as the task.

Sometimes, however, it is necessary to handle interrupts that can come in rapid succession, with a requirement to gather data at each interrupt, so that several interrupts may occur before the task that will process the data can be scheduled, and more interrupts may occur even while the task is running. This problem is best handled by establishing a queue of the interrupt data records. Then the only shared data between the interrupt handler and the task processing the data can be the queue head and tail pointers, which can be atomically updated. In the following toy example, the interrupt routine records the value returned by an arbitrary function, `get_data()`, each time the signal `SIGINT` is sent. A waiting task is then scheduled and prints all accumulated data.

```
class Delete_handler : public Interrupt_handler {
        void     interrupt();
        int*     localq;                      // data buffer beginning
        int*     localq_end;                  // data buffer end
        int*     localq_h;                    // queue head
        int*     localq_t;                    // queue tail
public:
        int      getX(int&);                  // the next item, if any
                 Delete_handler(unsigned local_q_size =5);
                 ~Delete_handler() { delete [localq_end - localq] localq; }
};
```

The delete handler (so called because `SIGINT` is normally sent when the user presses the **DELETE** key) is an interrupt handler that maintains a local queue of data. Its interrupt function will put data on the local queue, using `localq_t`, the queue tail pointer, and its `getX()` function is used by a task to retrieve the data.

```
Delete_handler::Delete_handler(unsigned local_q_size)
: (SIGINT)          // base class constructor arg
{
        localq_t = localq_h = localq = new int[local_q_size];
        localq_end = &localq[local_q_size];
}
```

The constructor initializes the local queue. The size of the local queue determines how many interrupts can be awaiting processing.

```
void
Delete_handler::interrupt()
{
        register int*   p = localq_t;
        *p = get_data();
        if (++p == localq_end) p = localq;
        if (p != localq_h)
                localq_t = p;          // no overflow
        else error("Overflow");
}
```

The interrupt function assumes that `localq_t` points to an available slot in the queue and puts the real-time data there. It then checks for overflow and updates `localq_t` to point to the next available slot if it's okay or calls an error function otherwise.

```
int
Delete_handler::getX(int& ans)
{
        register int*p = localq_h;
        if (p == localq_t)
                return 0;
        ans = *p;
        if (++p == localq_end) p = localq;
        localq_h = p;
        return 1;
}
```

The function `getX()` assigns the next datum to its argument and returns "1," or returns "0" and leaves its argument alone if no data is available. A call to `getX()` may be interrupted, but it has been designed so that no corruption of the queue will result.

```
class Delete_printer : public task {
        Delete_handler*handler;
public:
        Delete_printer();
};
```

`Delete_printer()` is a task that will create a `Delete_handler` and print whatever data is received.

```
Delete_printer::Delete_printer()
: handler(new Delete_handler)
{
        for (;;) {
                wait(handler);
                inti;
                while (handler->getX(i))
                cout << i << "\n";
        }
}
```

Note that each time the printer task is scheduled, it prints all the available data from the delete handler.

Implementation Details

The approach taken was to minimize the impact to the scheduler and to isolate as much as possible the machine and operating system dependent parts of the implementation. There is a system-dependent function, `sigFunc()`, which catches each signal for which an `Interrupt_handler` exists. When the signal is sent, `sigFunc()` calls the appropriate `interrupt()` function. It then atomically puts the address of a dedicated alerter task in a static, private cell of the scheduler and rearms the signal and returns. At the next entry to the scheduler, that cell is checked and if it is non-zero, the alerter task is scheduled. The alerter task alerts all pending interrupt handlers and returns to the scheduler. Tasks that were waiting for interrupt handlers are then eligible to run.

The other system-dependent parts of the implementation are the constructor and destructor for class `Interrupt_handler`. Its constructor takes the signal number as argument (it might be an interrupt vector address in another system). If some other interrupt handler already existed for that signal, it is saved (and alerted if it was pending), and otherwise the UNIX system function `signal()` is called to associate `sigFunc()` with the signal. The destructor undoes the action of the constructor, restoring the previous signal routine if necessary.

Example Programs

tcreate.c

The following program repeatedly creates a task and waits for it to terminate. It would be possible to time creation of new tasks without waiting for them to terminate, but because of the limited number of processes that can exist under the UNIX system, the corresponding UNIX system program would fail.

```
#include "task.h"

class Child : public task                       // user task declaration
{
public:
                Child(int);                     // task constructor declaration
};

Child::Child(int i)                             // user task constructor definition
: ("Child")                                     // argument to base class constructor
{
        resultis(i);                            // terminate task execution
}

main()
{
        for (register int i = 10000; i--; ) {
                Child*  c = new Child(i);       // create a task
                c->result();                    // wait for it to terminate
                delete c;                       // clean up
        }
        thistask->resultis(0);                  // exit from main task
}
```

ucreate.c

The following C program repeatedly forks a UNIX process and waits for it to terminate.

```
main()
{
        register int i;
        for (i=10000; i--; )
                if (fork() == 0)
                        exit(0);            // child process
                else
                        wait((int*)0);      // parent process
}
```

tswitch.c

The following program uses two semaphores (described under "Semaphores") to alternate control between a parent and child task.

```
#define K 10000
#include "task.h"

class Child : public task
{
public:
                  Child();
};

Semaphore sema1;                          // for signals from main to Child
Semaphore sema2;                          // for signals from Child to main

Child::Child()
: ("Child")
{
         for (register int n = K / 2; n--; ) {
                  sema1.wait();           // wait for a signal from main
                  sema2.signal();         // send it back
         }
         resultis(0);
}

main()
{
         new Child;
         sema1.signal();                  // send the first signal
         for (register int n = K / 2; n--; ) {
                  sema2.wait();           // wait for a signal from Child
                  sema1.signal();         // send it back
         }
         thistask->resultis(0);
}
```

uswitch.c

The following C program uses a UNIX system signal to force alternation between two UNIX system processes. The program is a little strange in that its main routine consists of an infinite loop of `pause()` calls. Unfortunately the utility of `wait()` and `pause()` for signal handling is limited because it is always possible that a signal has been received just as the `wait()` or `pause()` is being executed.

```
#include <signal.h>
#define K10000
int      otherpid;
int      received;
int      child;
void
sig()                                    /* signal-catching routine.  called */
                                         /* when a signal is received        */
{
         signal(SIGTERM, sig);           /* arrange to catch the next signal */
         received++;
         if (child && received >= K/2) exit();
         kill(otherpid, SIGTERM);        /* send it back */
         if (!child && received >= K/2) exit();
}

main()
{
         signal(SIGTERM, sig);           /* arrange to catch the signal */
         if ((otherpid = fork()) == 0) { /* create the child process */
                  otherpid = getppid();  /* get parent process id */
                  child = 1;             /* this is the child */
                  kill(otherpid, SIGTERM);  /* send the first signal */
         }
         for(;;)
                  pause();
}
```

real_timer.c

In addition to the robot application, the system was implemented on the UNIX Operating System using signals as interrupts. A class Real_timer, modelled on the original class timer was built.

```
class Real_timer : public object {
         friend class Alarm_handler;
         int      state;              // RUNNING, IDLE, TERMINATED
         long     time;               // initially delay, then alarm time
         void     insert(long);       // put on chain
         void     remove();           // remove from chain & make IDLE
         void     resume();           // called when time is up
public:
                  Real_timer(long);
                  ~Real_timer();
         int      pending();
         void     reset(long);
         void     print(int, int =0);
};
```

Instead of simulated clock ticks, class `Real_timer` measures time in seconds. It is based on the following handler for the alarm signal and a task that maintains the list of unexpired `Real_timer` instances.

```
class Alarm_handler : public task {
        friend Real_timer;
        Real_timer*             chain;
        Interrupt_handler*      bell;
        void                    add_timer(Real_timer*);
        void                    remove_timer(Real_timer*);
public:
                        Alarm_handler();
};

Alarm_handler       alarm_handler;              // the only instance

Alarm_handler::Alarm_handler()
: ("Alarm_handler"), chain(0)
{
        sleep();
        for(;;) {
                for (long now = time(0); chain && chain->time <= now;
                                        chain = (Real_timer*)chain->o_next)
                        chain->resume();    // alert the timer
                if (chain) {
                        alarm(chain->time - now);
                        wait(bell);
                } else {
                        bell->forget(thistask);
                        delete bell;
                        sleep();
                }
        }
}
```

The `Interrupt_handler` pointed to by `Alarm_handler::bell` only exists while there are pending `Real_timer` objects. The `Alarm_handler` task runs after an alarm signal, and after alerting any timers that have expired, if there are any unexpired timers, it resets the alarm and waits.

A Porting Guide for the C++ Coroutine Library

NOTE

This section is taken directly from a paper by Stacey Keenan.

Introduction

The C++ coroutine library, commonly known as the task library after its header file, `task.h`, provides multiple threads of control within one UNIX system process. Each thread of control is a coroutine, or task, and each task runs until it explicitly gives up the processor; there is no pre-emption. Implementing concurrency requires knowledge of hardware-dependent and compiler-dependent runtime features, especially calling sequence and stack frame layout; hence the library is target-dependent and must be ported explicitly to each supported compiler/processor platform.[16] The target-dependent parts of the library are isolated in four files. Release 3.0 of the C++ Language System supplies the task library for the AT&T 3B20, AT&T WE32000 family (e.g., 3B2, 3B15), AT&T 6386 WGS and DEC VAX processors, and the Sun-2 and Sun-3 Workstations (Sun compilers on Motorola 68000 family processors).

This paper describes the implementation of the task library, with particular emphasis on task creation and task switching, where target-dependent code is needed. The existing implementations for the 3B, VAX, and Sun Workstation processors are used as examples.[17] The scope of this paper is limited by the similarity of the runtime models supported by these targets. Targets diverging from these models, like mainframe or RISC–style processors, are likely to present porting difficulties not addressed in this paper. It is assumed that the reader has access to the source code for the library. This paper does not describe how to use the task library; see "A Set of C++ Classes for Co-routine Style Programming" and "Extending the C++ Task System for Real-Time Control" for user-level information. "Task Switching Fundamentals" provides background needed to understand the workings of the task library. "Implementation of Task Switching" describes how the task library creates new tasks and switches among them, including details about the target-dependent functions `swap()` and `fudge_return()`. The final sections discuss source file organization and miscellaneous hints for porting the library.

Task Switching Fundamentals

The C++ task library provides non-preemptive scheduling for tasks. A task runs until it explicitly gives up the processor to allow another task to run. Typically, a task will give up the processor when it tries to perform an action that cannot yet be done, for example, if it tries to put an object on a full queue, or to get an object from an empty queue. When this happens, the task is put to sleep.[18] The scheduler then chooses to run the next task on the ready-to-run list, `sched::runchain`.

When a task is put to sleep, or suspended, the task system must save the state of the task so that it may be resumed later. On the targets described here, this involves saving the task's stack and hardware registers, including the non-volatile registers and the frame pointer (and the argument pointer on some targets). A task switch is the process of saving the state of one task, and restoring the state of another.

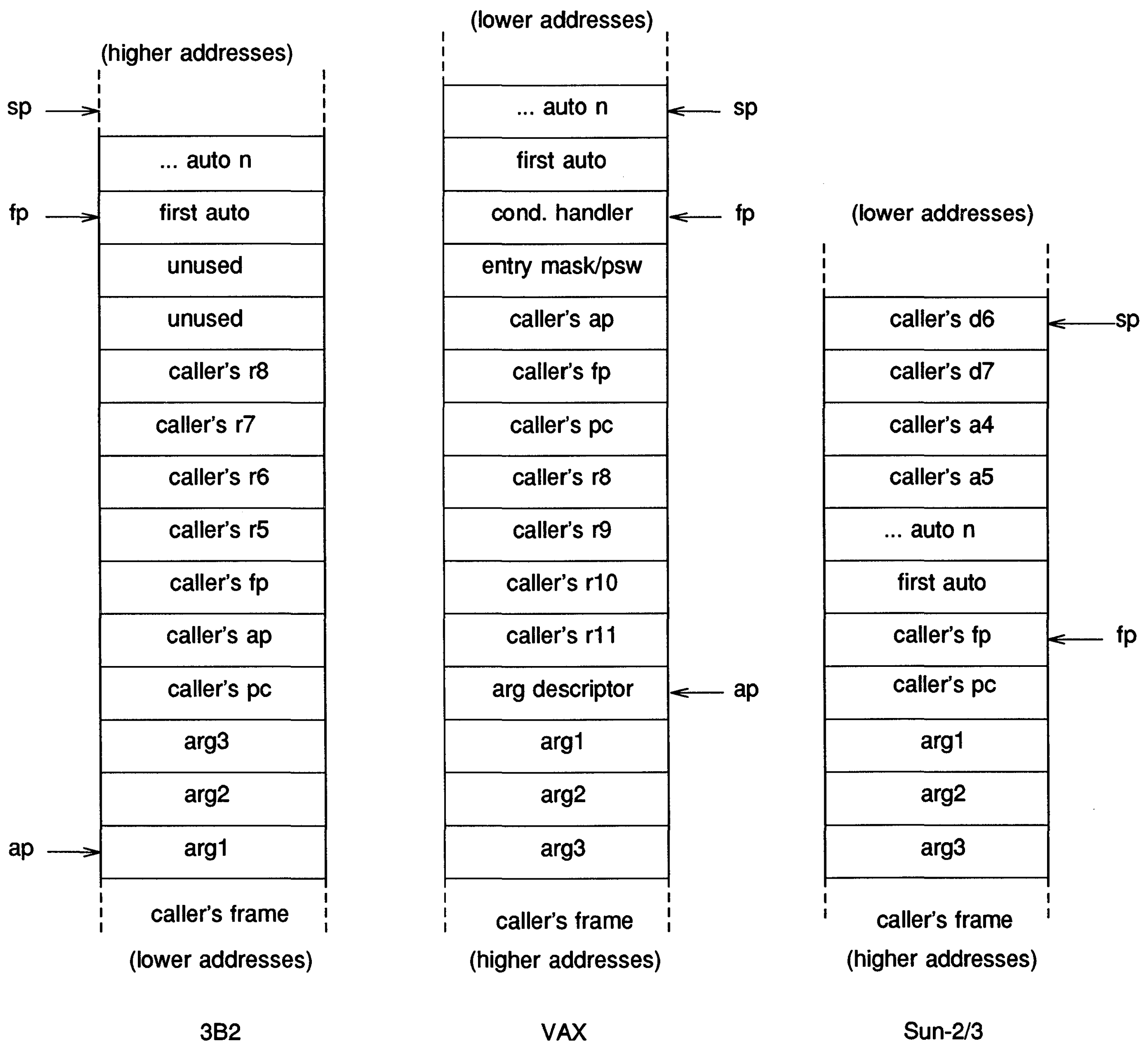
Stack Frames

Some familiarity with the C runtime environment and the target implementation of stacks is needed to understand the details of task creation and switching. A C function call sets up a new stack frame for the function. A stack frame contains the arguments to the function, the saved hardware state of the calling function, and any automatic variables used by the function. Figure 2-1 illustrates the stack frames built on the 3B2, the VAX, and the Sun-2/3 targets for a function called with three arguments and saving four registers. These stack frames are described here to provide a base for later discussions on the internals of the task library.

On a 3B2, the argument pointer (ap) points to the start of the arguments to the function, the frame pointer (fp) points to the start of the automatics of the function, and the stack pointer (sp) points to the next available space in the stack. The caller's registers are saved between the arguments and the automatics. Previous stack frames can be accessed via the frame pointer: The old frame pointer, argument pointer, and program counter (pc) are always a fixed distance below the frame pointer. Stacks grow up, toward higher memory addresses.

On a VAX, stacks grow down, toward lower memory, although the figures in this paper will show the low memory on top and relative positions on the stack will be described in terms of the pictures (e.g., above means higher in the picture, at a lower memory address). The argument pointer points to a longword containing the number of arguments that have been pushed on the stack. Arguments are pushed in reverse order, so that the first argument is stored one word below the ap. The frame pointer points to a condition handler, above which are the automatics of the function. The stack pointer points to the last assigned word in the stack. The word just under the frame pointer contains a procedure entry mask, which tells which registers were saved in the frame. Saved user registers and the old frame pointer, argument pointer, and program counter are stored between the argument and frame pointers.

Figure 2-1: Stack Frames on a 3B2, a VAX, and a Sun-2/3 for a Function Taking 3 Arguments and Saving 4 Registers



The stack on the Sun-2/3 Workstation grows down, toward lower memory. This target has no argument pointer. Arguments, saved registers, and automatics are all referenced as offsets from the frame pointer. Arguments are pushed on the stack in reverse order, followed by the return pc and the old frame pointer. The frame pointer points at the old frame pointer. Space for automatics is reserved above the frame pointer. Saved registers are pushed after the reserved space, and the stack pointer points to the last saved register. The 68000 processor has both data (d*x*) and address (a*x*) registers. In this example, two of each type are saved.

On entry, a function first saves all the registers that it might use.[19] On function exit, the same number of registers are restored from the register save area of the stack frame. On some targets, like the VAX, stack frames are self-describing: one can tell how many registers are saved in the frame (and where they are) from the frame itself (by looking at the entry mask). Thus, the function return sequence on a VAX consists of a single, simple instruction: `ret`. The 3B and Sun-2/3 targets do not have self-describing stack frames. This means that "return" instructions on these targets need to specify how many registers to restore. When (as happens in the task system) one needs to restore registers without returning through the normal return sequence, one can only find out how many registers were saved on the stack by looking at the save instruction at the beginning of the function.

To switch to a new task, the task system needs to know what the new frame pointer (and argument pointer on the 3B targets) should be and from where to restore all the non-volatile registers.[20] The task library explicitly saves the frame pointer and argument pointer of the function to be returned to, `swap()`, in the task object as `t_framep` and `t_ap`. The non-volatile registers are stored in `swap`'s stack frame.

DEDICATED and SHARED Tasks

Tasks can be of one of two modes: DEDICATED or SHARED. DEDICATED tasks each have their own stack, of some fixed size, allocated from the free store. SHARED tasks share a single stack, of some fixed size. When a SHARED task is about to resume execution, if its stack space is occupied by another task,[21] the portion of the stack that is in use by the other (suspended) task is copied out to a save area, and the resuming task's stack is copied from its save area back into the stack. Because the in-use part of the stack is less than the allocated size of the stack, the user can save space by using SHARED stacks, at a cost in execution speed. Additionally, some targets and operating systems do not allow the stack pointer to point into the UNIX process data segment; on these systems SHARED tasks must be used.[22]

Implementation of Task Switching

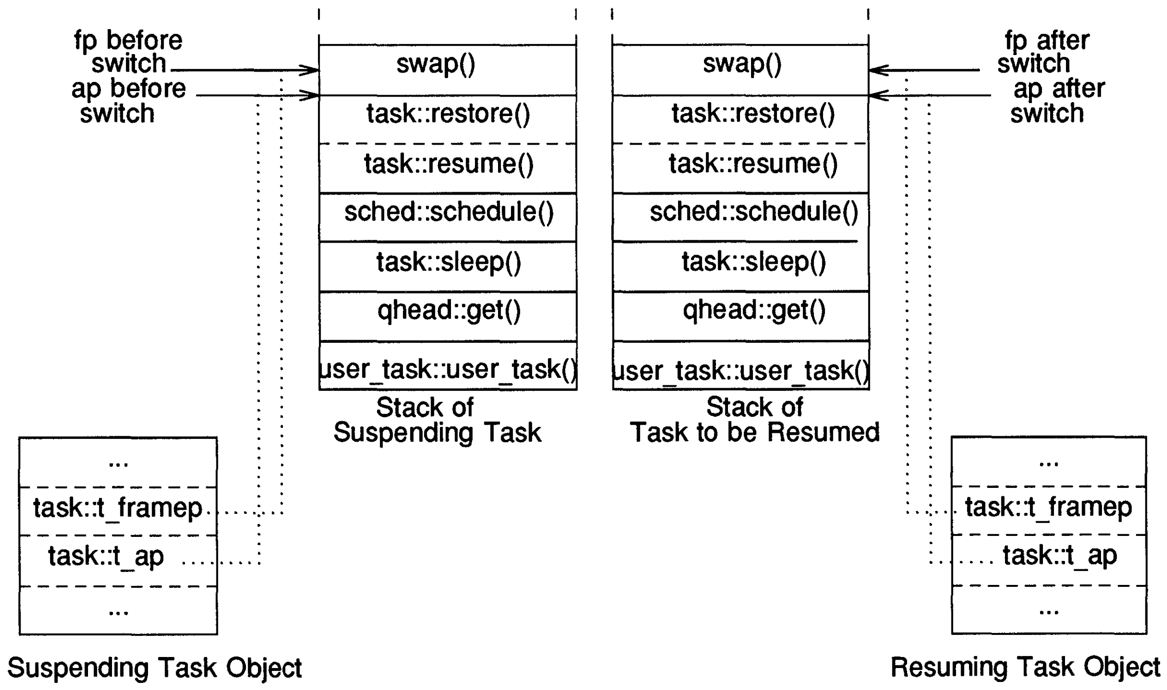
There are two general contexts in which a task switch occurs: when a parent task creates a new child task and switches to it, and when a task suspends and the scheduler chooses a new task to run. The stacks of both the suspending and resuming tasks look different in each of these situations. Task creation differs from a switch to a suspended task in two ways. First, in task creation a runtime environment for the new task must be set up before the switch can take place. Second, task creation causes the parent task to be suspended and the new task to run immediately, bypassing any other tasks waiting on the run chain. This is the only case where a task switch takes place without a call to the scheduler to choose the next task to run. These two contexts are described below.

Task Switches Between Suspending and Resuming Tasks

In task switches from a suspending to a resuming task (i.e., switches other than those to newly created tasks), the function that causes the running task to block (`qhead::get()` in Figure 2-2) calls `task::sleep()`, which in turn calls the scheduler, `sched::schedule()`. After selecting the next task to run, the scheduler calls `task::resume()`[23] for the resuming task. The function `task::resume()` calls `task::restore()`, an inline function whose purpose is to call the appropriate version of `swap()` (`swap()` for `DEDICATED` tasks, `sswap()` for `SHARED` tasks) with the appropriate arguments.

Figure 2-2 shows examples of the stacks for a suspending and a resuming task, both of type `user_task` (`user_task::user_task()` is the constructor and "main" function of the task). Each box in the stack represents a stack frame; the frames for `task::resume()` and `task::restore()` are separated by a dashed line because `task::restore()` is an inline function, and therefore doesn't really have its own stack frame.

Figure 2-2: A Task Switch from a Suspending to a Resuming Task (DEDICATED)



Switching Between DEDICATED Tasks: `swap()`

The two `swap` functions do the real work of performing a task switch. They are written in assembly language because they manipulate hardware registers. The `swap()` function saves the state of the suspending task (labeled `running` in the code)[24] and restores the state of the resuming task (labeled `to-run`). Saving the state of the suspending task involves first saving all the non-volatile registers in `swap`'s stack frame, then saving the current frame pointer, which defines `swap`'s frame, and the argument pointer, if necessary, in the suspending task's task object, in members `t_framep` and `t_ap`. Then `swap()` overwrites the hardware frame pointer and argument pointer with the values saved in the resuming task's `t_framep` and `t_ap`. Now the to-run task is running; `swap()` returns, restoring all the registers that were saved when the to-run task was suspended. Note that `swap`'s save is done on the suspending task's stack, and the restore is done on the resuming task's stack. This is because save and restore instructions are executed relative to the frame pointer, which was modified in the middle of `swap()`. Figure 2-2 illustrates a task switch on a 3B target. The `swap()` hardware frame and argument pointers are shown both before and after the switch.

Switching Between SHARED Tasks: `sswap()`

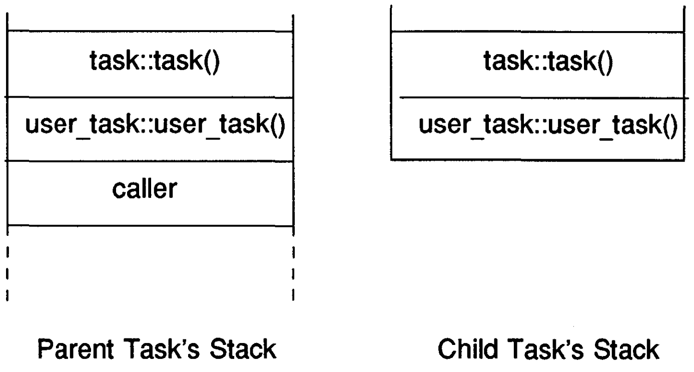
The function `sswap()` is like `swap()`, but has additional code for SHARED tasks to copy task stacks out of and into the shared stack area.[25] There are three tasks that are relevant during a SHARED task switch: the suspending task, the resuming task, and the task that last occupied the stack space that the resuming task now wants to occupy (the target stack). This "prevOnStack" task is often the same as the suspending task, but that is not necessarily the case.[26]

The `sswap()` function first saves all the non-volatile registers in its stack frame, then saves the frame pointer (and argument pointer, if necessary) of the suspending task in that task's task object, just as `swap()` does. It also calculates and saves the height of the stack in the `t_size` member of the task object. Next, it allocates space and copies the contents of the target stack to that space, which becomes "prevOnStack's" save area (pointed to by task member `t_savearea`). Next, `sswap()` copies the resuming task's saved stack back from its `t_savearea` to the target stack, and deletes the space. Finally, `sswap()` restores the resuming task's `t_framep` (and `t_ap`, if necessary) to be the hardware frame and argument pointers, and the resuming task is running. As in `swap()`, `sswap()` returns, restoring all the registers saved in the resuming task's `sswap` frame.

New Task Creation

To use the task library, the user derives a class, which I will refer to as class `user_task`, from the base class `task`. The "main" program for the user task will be the constructor `user_task::user_task()`. The first thing `user_task::user_task()` does is to call the base class constructor, `task::task()`. The constructor `task::task()` initializes the private data for the new task, acquires stack space[27] in which the task will run, initializes the stack with the top two frames of the parent task's stack (as illustrated in Figure 2-3), inserts the parent task on the run chain, and switches to the new task, which runs immediately.

Figure 2-3: Creating a New Task's Stack



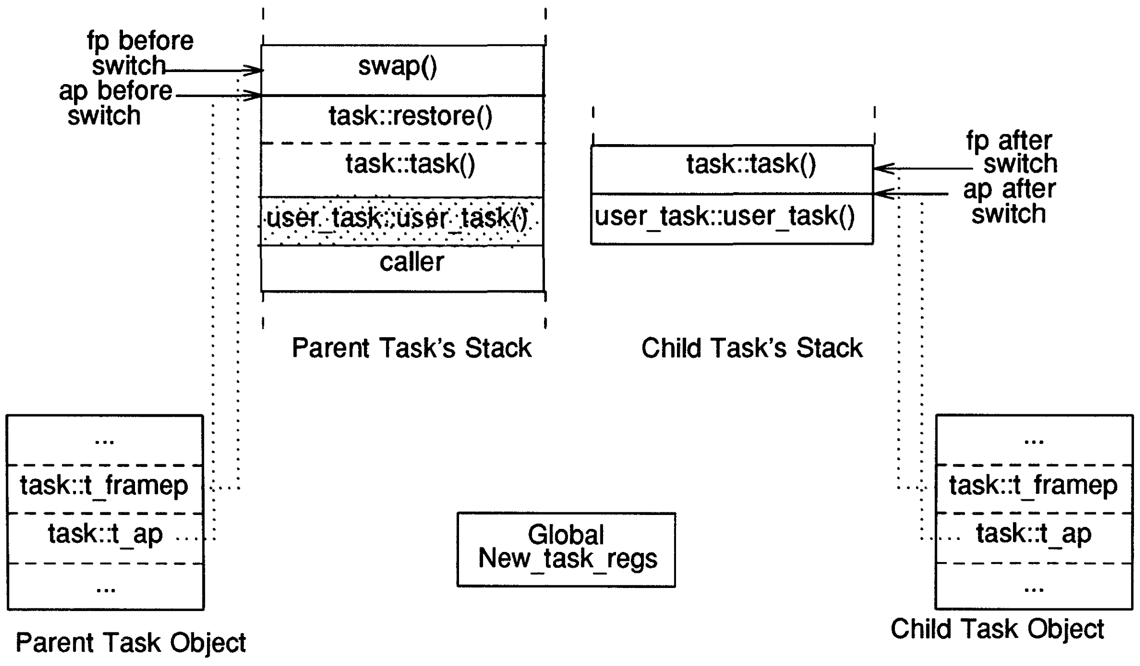
After initializing the new task's stack, the parent task continues execution in `task::task()`. Notice that the parent's stack contains a frame for `user_task::user_task()`, the child's "main"; the parent task needs to skip over that frame when it returns from `task::task()`. To arrange this, `task::task()` calls a function, `task::fudge_return()`, to alter `task::task`'s stack frame so that it returns to `user_task::user_task`'s caller (restoring any registers saved in the skipped frame as well). This change to the parent's stack is shown in Figure 2-4 with dotted lines through the `user_task::user_task()` frame. The `fudge_return` function will be described in detail under "Fudging the Parent Stack."

`swap()` for Children

When a new task is created, its stack does not have an instance of `swap()` on it; `task::task()` is the top frame. It is `task::task`'s responsibility to arrange for the hardware state of `user_task::user_task()` to be restored when the child begins execution there. Therefore, `task::task()` saves the frame and argument pointers for the child's `task::task()` frame in the child's `t_framep` and `t_ap` of its task object. Then `task::task()` saves all the registers as they were when `user_task::user_task()` called `task::task()` in a global variable, `New_task_regs`.[28] Getting these registers right, no matter how many registers were saved in `user_task::user_task` or `task::task()`, is a bit tricky. We first copy all the current hardware registers into `New_task_regs` and then overwrite any of those that are used by `task::task()` with those saved in `task::task`'s frame. This is done with a macro, `SAVE_CHILD_REGS`, which calls `SAVE_REGS()` to do the first step, and `save_saved_regs()` to do the second step.

Then the parent calls `task::restore`, which calls `swap()` with a `NEW_CHILD` argument. Given this argument, `swap()` explicitly restores the registers that were saved in `New_task_regs`, instead of restoring the registers saved in the frame. See Figure 2-4 When `swap()` returns, the return is effectively from `task::task()`, as that is where the frame pointer points, and then the child task is executing in `user_task::user_task()`. On the 3Bs, the assembly language return instruction specifies how many registers to restore. Because the necessary registers have been restored from `New_task_regs`, `swap()` restores no registers saved in `task::task()`'s frame on its return. The VAX return instruction determines the number of registers saved in the frame by looking at the entry mask under the frame pointer, therefore, when `swap()` returns, the registers saved in `task::task`'s frame are restored. Since these registers are the same as those saved by `save_saved_regs()`, `save_saved_regs()` is unnecessary on the VAX.

Figure 2-4: A Task Switch to a New Child (DEDICATED)



`sswap()` for Children

New SHARED tasks don't need to copy in a new stack, nor do they need to reset the hardware frame and argument pointers. Their stacks are already in place, since a new SHARED task runs in its parent's stack. However, the parent task needs to call `sswap()` to save its state and to copy its active stack to its save area. Therefore, `task::restore()` and `sswap()` are called with a NEW_CHILD argument, and `sswap()` has a branch for new children to skip the "copy in" part.

Fudging the Parent Stack

As mentioned above, `fudge_return` is called by `task::task()` to modify the parent stack so that the parent does not return to `user_task::user_task()`. Rather, the parent skips the `user_task::user_task()` frame and returns to `user_task::user_task`'s caller (`main()` in Figure 2-4). This routine is highly machine- and compiler-dependent. It depends on call/return and save/restore conventions of both the compiler and the machine. The left side of Figure 2-5 shows a hypothetical example of a parent stack when `fudge_return()` is first called. Portions of three stack frames are shown:

- at the bottom is the register save area for `user_task::user_task()`, containing the saved state of `main()` (i.e., "main's r8" refers to the value of hardware register r8 in `main()` before `user_task::user_task()` was called). In this example, `user_task::user_task()` uses, and therefore saves, two registers, which on a 3B2 would be registers r7 and r8.

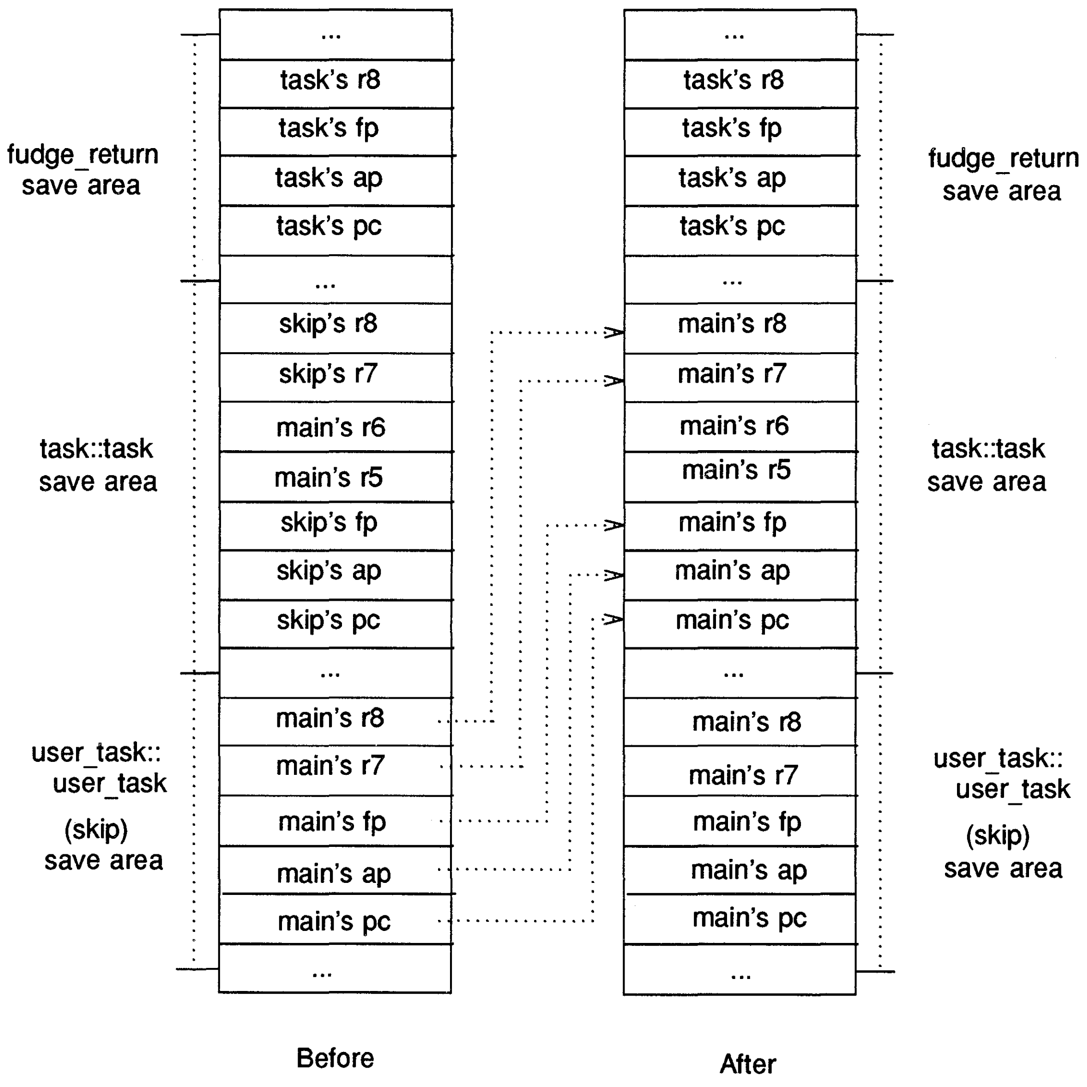
- in the middle is the save area for `task::task()`, containing the saved state of `user_task::user_task()` or `skip()`, as it is labeled in the diagram and in the `fudge_return()` code. In this example, `task::task()` uses and saves four registers, r5 through r8.[29]
- at the top is the save area for `fudge_return()`, containing the saved state of `task::task()`. In this example, `fudge_return()` uses and saves just one register, r8.

The ellipses in the diagram represent function arguments, automatics, and unused words in the stack frames. The `fudge_return()` function must copy up the relevant elements from `skip`'s stack frame to `task::task`'s stack frame, so that when `task::task`'s return instruction is executed, the parent will find itself back in `main()` (in this example), with the hardware registers restored to the values they had before `skip()` was called. The stack on the right side of Figure 2-5 represents the same parent stack after `fudge_return` has altered the stack. The dotted arrows show where the elements from `skip`'s save area have been copied.

In the 3B, VAX, and Sun-2/3 implementations, `fudge_return()` overwrites the program counter, frame pointer, and argument pointer (for 3B targets only) saved in `task::task`'s frame with those saved in `skip`'s frame. This causes `task::task()` to return to `main()`.

Restoring `main()`'s registers is trickier. It requires knowing the layout of the save area for at least `skip()` and `task::task()`, and sometimes for `fudge_return()` as well. Ways of determining the frame layout are discussed under "Finding Where Registers Are Saved: Framelayout()." For now, assume `fudge_return()` knows how many registers are saved in each frame.

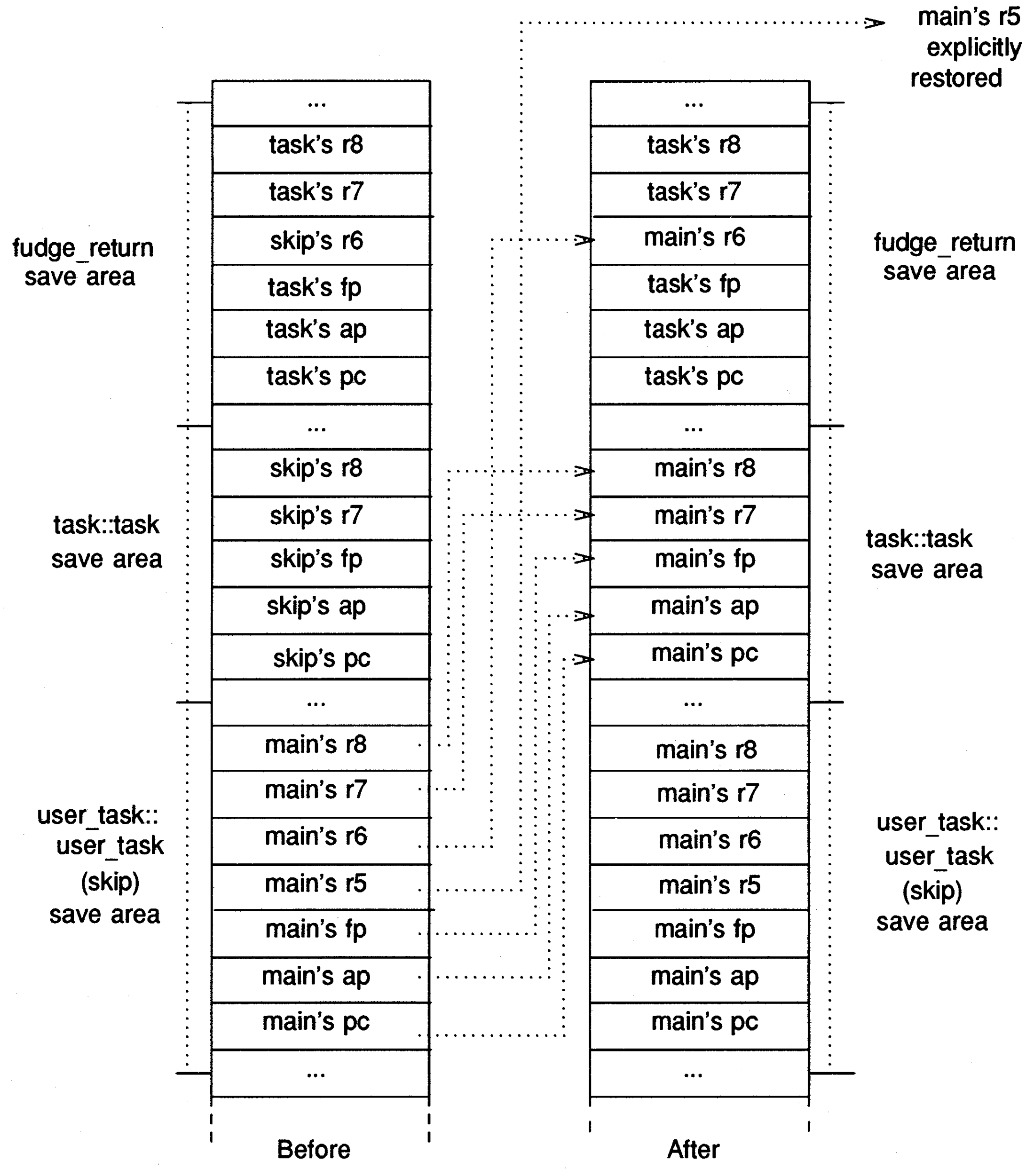
Figure 2-5: A 3B2 Stack Before and After Fudging



If `skip()` saved any registers, we must take pains to see that they are restored on `task::task`'s return. If, as is the case in the example in Figure 2-5, all the registers saved in `skip`'s frame are also saved in `task::task`'s frame, this is simple. We just copy the saved `skip()` registers over the corresponding `task::task()` registers, leaving any additional saved `task::task()` registers in place. There is room in `task::task`'s frame for these registers and, in the case of the 3B and Sun-2/3 targets,[30] `task::task`'s restore instruction will restore all the registers we care about.

There are various difficulties with restoring the "extra" registers when `skip()` saves registers that `task::task()` does not save. On some targets, such as the VAX and Sun-2/3, there is no room in the frame for the additional registers; on other targets, such as the 3Bs, `task::task`'s restore instruction won't restore any extra registers, although the save area is always large enough to hold extras. Figure 2-6 shows a parent stack frame where the `skip()` frame contains four saved registers, the `task::task` frame contains only two saved registers, and the `fudge_return()` frame contains three saved registers. In this example, r5 and r6 are "extra."

Figure 2-6: Fudging When `user_task::user_task()` **Uses More Registers than** `task::task`



If fudge_return() saved any of the "extra" registers, then we can overwrite those with the corresponding saved skip registers. In Figure 2-6, skip() saved r6 ("main's r6"), task::task() did not, but fudge_return() also saved r6. Therefore, fudge_return() will overwrite the r6 in its save area with the r6 from skip's save area. When fudge_return() returns, r6 will be restored to the value it had when main() last executed, which is what we want. Because task::task() did not save r6, we know that it will not disturb its value.

Neither task::task() nor fudge_return() saved the other extra register, r5, in this example. Therefore, to ensure that when task::task() returns, r5 has the value it had in main(), and not the value it had in skip() (its current value), fudge_return() must explicitly set the hardware register r5 to the value saved in skip's frame (main's r5). This is safe to do, because none of the intervening functions use r5. The function fudge_return() calls an assembly language function to overwrite r5 (or any other extra registers). After fudge_return() and task::task() return, all the registers will have the values they had when main() last executed on the parent stack.

There is one final step: arranging for the stack pointer to be in the right place after task::task returns. This depends on the way the target executes a return. Without some adjustment, the stack pointer will be set one frame too high (at the top of skip's frame instead of at the top of main's frame).

On the VAX, a return instruction restores the frame and argument pointers from those saved in the stack, pops the saved registers off the stack, and adds the number of arguments that are on the stack (as given in the argument descriptor, see Figure 2-1) to the stack pointer. We can cause the stack pointer to be restored correctly by adjusting the argument descriptor in task::task's frame to include all the words in the skip frame in addition to the arguments. In other words, fudge_return() alters task::task's frame to look as though there is a big argument list.

On the 3Bs, a return instruction restores the frame and argument pointers from those saved on the stack, but the stack pointer is given the value of the argument pointer of the returning function. This presents a problem for a fudged parent stack: when we return from task::task(), the frame and argument pointers are reset to point to main's frame, as we wanted, but the new stack pointer points where task::task's argument pointer was, which is higher than needed and wastes space.[31] What we want is to have the stack pointer point to where skip's argument pointer was. We arrange for this with an assembly language function, FUDGE_SP(),[32] which is defined for the 3Bs to take an argument, the skip() argument pointer, and to reset the current argument pointer (task::task's) to the argument. FUDGE_SP() is called just before task::task() returns on the parent side. Once FUDGE_SP() is called, no arguments to task::task() can be referenced. The task::task() constructor returns the this pointer, which is its implicit first argument. The this argument is usually in a register, but if it is not, task::task will need to reference it through the now-changed argument pointer when it sets the return value. Therefore, FUDGE_SP() also copies the value of task::task's first argument to be user_task::user_task's first argument, to ensure that task::task's return value will be set properly.

The Sun-2/3 targets have a similar problem to that described above for the 3B targets. The solution, however, is different. The Sun-2/3 compiler typically generates a function return sequence of three instructions: movem, unlk, and rts. The movem instruction restores the registers denoted by a mask and uses an offset from the frame pointer to find the register save area. The unlk instruction resets the frame pointer to be the one saved in the stack, and also resets the stack pointer to point at the saved return program counter on the stack. Finally, the rts instruction pops the program counter off the stack, leaving the stack pointer pointing at the top of the frame of the function that called the returning function. As with the 3B targets, after a parent task (whose stack has been fudged) returns from `task::task()` to `main()` (in the example), the stack pointer points to the top of the skipped frame.

We compensate for this with a variation in `FUDGE_SP()` and `fudge_return()` on the Sun-2/3 targets.[33] Instead of overwriting `task::task`'s return pc with `skip`'s return pc, `fudge_return()` overwrites `task::task`'s return pc with the address of an assembly language function, `fudge_sp()`. When the parent task returns through `task::task()`, it calls `FUDGE_SP()`, which sets a global variable, `Skip_pc_p`, to point to `skip`'s return pc in the stack. Then `task::task()` returns to `fudge_sp()`,[34] which sets the stack pointer to `Skip_pc_p`, and executes an `rts` instruction, which pops `skip`'s saved return pc off the stack, leaving the stack pointer at the top of `main()`'s frame.

Finding Where Registers Are Saved: `FrameLayout()`

As mentioned above, fudging the parent stack requires knowing the layout of the stack frames surrounding the one to be fudged.[35] This is not a problem for targets with self-describing stack frames, such as the VAX. Targets that do not have self-describing stack frames, such as the 3B and Sun-2/3, include a structure, defined in the source file `fudge.c`, called `FrameLayout`. `FrameLayout` has different members, depending on the target. It always has a constructor, which initializes the members so that `fudge_return()` has the information it needs to modify the parent stack.

`FrameLayout` for the 3B Processors

On the 3B2 and 3B20 targets the layout of saved registers follows from the number of registers saved by the function. On both targets, the size of the save area is invariant; if fewer than all the registers are saved, some slots in the save area will be unused and contain garbage values. The number of registers saved is found by looking at the save instruction of the function in question. By convention, the save instruction is the first instruction of the function. The easiest way to find the save instruction for a given function, *f*, is by dereferencing a pointer to the function. However, when *f* is a constructor, as both `task::task()` and `user_task::user_task()` are, one cannot take its address. In this case, one can find the save instruction for *f* by using the pointer to the return pc saved in the *f*'s frame, backing up one instruction to find the instruction to call *f*, and following the destination argument of the call to find the save instruction.

On the 3B targets, `Framelayout` contains one element: `n_saved`, which represents the number of registers saved in the frame. The `Framelayout` constructor finds `n_saved` for the frame denoted by its frame pointer argument. `FrameLayout::FrameLayout()` uses the frame pointer to find the return pc, which points to the instruction after the call to the denoted function. It backs up one instruction to get a pointer to the call instruction,[36] then decodes the call instruction (using a function called `call_dst_ptr()`) to get a pointer to the function denoted by the frame pointer argument. Finally, it decodes the save instruction (pointed to by the function pointer) to find the number of registers saved in the frame.

`FrameLayout` for the Sun-2/3 Target

On the Sun-2/3 target, `Framelayout` contains two elements: `offset`, the offset of the top of the register save area from the frame pointer, and `mask`, the bit mask denoting which registers were saved. The `Framelayout` constructor for the Sun-2/3 initializes the structure by a method similar to that described above for the 3B targets, which involves following the return pc to find the call, and decoding the call to find the destination of the call. Finally, it decodes the instructions in the function prologue (which can vary), to find the `mask` and the `offset`.

Source File Organization

The target-dependent parts of the task library are isolated in four source files:

`hw_stack.h`
: contains target-dependent macro, const, structure, and function declarations for each supported target (surrounded by `#ifdef`s).

`hw_stack.c`
: contains definitions of target-dependent functions for each supported target (surrounded by `#ifdef`s). Many of these are short assembly language functions which set or return hardware registers.

`fudge.c`
: There is a version of `fudge.c` for each supported target, currently: `fudge.c.3b`, `fudge.c.vax`, `fudge.c.386`, and `fudge.c.68k`.[37] These files contain definitions of `task::fudge_return()` and `FrameLayout::FrameLayout()` (for the targets that need it).

`swap.s`
: There is a version of `swap.s` for each supported target, currently: `swap.s.3b`, `swap.s.vax`, `swap.s.386`, and `swap.s.68k`. These files contain the assembly language functions `swap()` and `sswap()`.

Hints for Porting the Task Library to Other Processors

- Draw pictures (like those in Figure 2-1) of the stack frame layout for the target to which you are porting. Detailed pictures of the register save areas of several frames on the stack, like those in Figure 2-5 and Figure 2-6, are helpful in writing `fudge_return()`.
- Become familiar with the sequence of operations in function calls and returns. Write and compile some sample C or C++ programs and look at the generated code to see what kinds of call and return sequences the compiler generates, in what order registers are used, and so forth. A fast way to write the copy in and copy out loops for `sswap()` is to write them in C, compile them with the `-S` option, and transcribe the generated code into `sswap()`.
- The implementation of the task library was designed to be both maintainable and, as far as possible, portable across both machines and compilers. These goals are sometimes mutually exclusive, and in those cases, we aimed for maintainability and portability across different compilers for the same machine (where possible). Some porters may want to write some of the assembly language functions in `hw_stack.c` as macros that depend on positional parameters and compiler conventions. For example, `FP()` returns the frame pointer for the calling function. This could also be written for the 3B targets as a macro that takes as an argument the first automatic variable of the function and returns the address of that variable, or for the VAX takes the same argument and returns the address of that variable minus one. This only works if the macro is given the `first` automatic as an argument, if the compiler assigns automatics in the order in which they are declared, and if the optimizer leaves the automatic on the stack, even if it is never read nor written.

Footnotes

1. The original version of this paper was written in 1980 by B. Stroustrup and revised in 1982 by him. Since then both the task library and C++ (then known as "C with Classes") have changed substantially, but the interface to the task library has been left intact. This has allowed old programs to run with new versions of the library, but has prevented any updating of the style of the interface, which does not conform to current tastes.

   This version of the paper has been revised by J. E. Shopiro to reflect the present state of affairs. I have added a few notes (in sans-serif type) where changes have been significant, and have made numerous syntactic changes, etc., without further comment.

2. Many of the member functions are inline, but their definitions are not shown here to prevent clutter. Class `task` is derived from class `sched` which is derived from class `object`. Class `object` is a simple base class used by most classes in the task system. It contains some of the pointers used by the task system's internal "house-keeping." Class `object` is described under "The `object` Class."
3. The class may have other member functions, of course, which may be called by the constructor or by any other function according to the usual rules of C++.
4. When the first task is created, `main()` automatically becomes a task itself.
5. It is a fairly simple job to add a new kind of task that returns some other datatype.
6. The handling of run time errors will be described below.
7. Thus `qhead::pending()` returns 1 if the queue is empty and 0 otherwise. Correspondingly, `qtail::pending()` returns 1 if the queue is full and 0 otherwise.
8. The default maximum size for a queue is 10000. That is, the queue can hold up to 10000 pointers to objects. It does not, however, pre-allocate space.
9. The original task package had a number of global variables, including `thistask`, `task_chain`, and `clock`. They are now all macros which expand to inline functions that return the values of private static variables. Thus programs that just read the values will be unaffected, but programs that try to set them (which was always illegal) will fail to compile.
10. `waitlist()` is an example of a function whose form does not satisfy current esthetic standards.
11. In a quasi-parallel system this will only be true provided no infinite loop without task system calls exists. Such a loop constitutes an error that only a system with true parallelism or time slicing can recover from.
12. Coroutines can exchange control among themselves more freely than ordinary functions and procedures. In the usual function calling discipline, when one procedure (more precisely, one instance of a procedure) executes a procedure call, a new instance of the called procedure is created, and the calling procedure waits until the called procedure (and any procedures *it* may call) returns. A procedure instance is initiated when the procedure is called and is destroyed when it returns. When one coroutine (coroutine instance) initiates another it need not wait for the new coroutine to end, but instead it can be resumed while the new coroutine is still active. A running coroutine can relinquish control to any waiting coroutine without abandoning its state and later regain control and continue from where it left off.

13. Class `object` is the base class of most classes in the task system. We use the `typewriter` font for programming language constructs.
14. Semaphores which are used for mutual exclusion are initialized with one excess signal so that the first lock call will succeed.
15. But watch out for deadlock.
16. To the extent that the target hardware dictates subroutine linkage and stack frame layout, the compiler is less important. Some machines, like the 3Bs and the VAX, support a particular stack frame; the task library is largely independent of the compiler on these machines. The 68000, however, does not support a specific stack frame arrangement; the task library on this machine also depends on the compiler conventions for the stack frame. The word *target* will be used in this paper to denote an instance of either a processor or a compiler/processor platform.
17. The stack frame layout on the AT&T 6386 WGS is similar to that on the Sun-2/3 Workstations. The task library port is also similar on these targets.
18. See "A Set of C++ Classes for Co-routine Style Programming" or "Extending the C++ Task System for Real-Time Control" for details. The ways in which a task is put to sleep and awakened are target-independent.
19. This is true for our example targets. Some targets may use a caller save convention rather than a callee save convention.
20. It may not be immediately obvious that *all* registers must be saved on a task switch. Consider a task A, which has a function *f* that uses all the registers. It calls another function, *g*, which uses less than all the registers, say two, and therefore only saves two registers in its save area. If a task switch occurs before *g* returns, and task B uses all the registers, it will destroy those needed by task A's function *f*.
21. It can happen that a `SHARED` task will resume execution without having ever been displaced by another task sharing the same stack.
22. For example, `DEDICATED` tasks do not work with 3B2s running versions of the UNIX system earlier than SVR3.
23. The function `resume()` is virtual, with definitions for tasks and timers. Only tasks are relevant here.
24. If the suspending task is `TERMINATED`, then `swap()` does not save its state.
25. Writing the code for stack copying of `SHARED` tasks in assembly language adds more complexity than we would like to the job of porting the task library. It would be possible to call a C function to copy out the suspended task's stack to its save area. However, copying the resuming task's stack back in presents a problem: If the resuming task's stack is taller than the stack on which we are executing, a copy-in will overwrite the current stack frame. The `sswap()` function is careful to move all the data it needs from the frame into registers, so that if the frame is overwritten, `sswap()` can still complete successfully. But if `sswap()` called a C function to do the copy-in, that function might overwrite its own stack frame, making it impossible to return to `sswap()` to finish the task switch. So long as the copy-in must be written as part of `sswap()`, it seems little more trouble to write the complementary copy-out in assembly language as well.

26. When the prevOnStack task and the resuming task are the same, `restore()` calls `swap()`, rather than `sswap()`, to do the task switch, as no stack copying is necessary.

27. The constructor `task::task()` only acquires stack space for `DEDICATED` tasks, that is, tasks that have their own stack. `SHARED` tasks will need space in which to save the current (or parent) task's active stack; `sswap()` takes care of that, as described above.

28. Only one child is activated at a time — remember, no pre-emption — and the child runs immediately, so it is safe to put these registers in a global, and more space-efficient than keeping them as part of the task object.

29. Note that, in Figure 2-5, the saved r5 and r6 in `task::task`'s frame are labeled "main's r5" and "main's r6" rather than "skip's r5" and "skip's r6." This is because in this example, `skip()` does not use r5 or r6; `main()` was the last function to use r5 and r6. Therefore, the values of r5 and r6 saved in `task::task`'s frame are the values that r5 and r6 had when `main()` was running.

30. The restore instruction for the VAX doesn't specify which registers to restore.

31. In the case of a task that repeatedly spawned children, the stack pointer would grow unnecessarily, eventually causing the stack to overflow. Each time the parent task returned from `task::task`, the stack pointer would be an additional frame higher than needed, and a new call to `task::task` would start building the next frame where the stack pointer pointed.

32. `FUDGE_SP()` is defined as a do-nothing macro for the VAX.

33. The AT&T 6386 WGS port of the task library also uses this technique.

34. When `task::task()` returns, the hardware registers are restored to the values they had in `main()` and the frame pointer is set to the value it had in `main()`, but the program counter is set to `fudge_sp()`.

35. Some of these frames are for user functions, so we cannot rely on techniques which require the C++ code for the function to be written so as to generate code that creates frames with some particular layout.

36. Because 3B instructions can be of various sizes, one cannot deterministically "back up" one instruction. `FrameLayout::FrameLayout()` subtracts each possible instruction size from the return pc and decodes the resulting pointer to check for a call opcode and legal operands. There is a small possibility, reduced by familiarity with the compiler, that these heuristic methods could yield more than one candidate call instruction.

37. The .68k suffix used for the Sun-2/3 target is something of a misnomer. These files were written specifically for Sun compiler/68K platforms; they will not necessarily work on all 68K platforms, for example, the AT&T compiler for the 68K. However, the `#ifdefs` in the source files say `#ifdef`mc68000

3 Iostream Examples

Iostream Examples

NOTE

This chapter is taken directly from a paper by Jerry Schwarz.

Abstract

The iostream library supports formatted I/O in C++. This document, containing many examples, is an introduction to the library. Overloading and other C++ features are used to provide an interface that combines flexibility and type checking. Predefined and user defined operations are easily mixed. The streambuf class supports alternate sources and sinks of characters.

The manual pages for the iostream library can be found at the end of this book.

Introduction

C and C++ share the property that they do not contain any special input or output statements. Instead, I/O is implemented using ordinary mechanisms and standard libraries. In C this is the stdio library. In C++ (since Release 2.0 of the AT&T C++ Language System) it is the iostream library. Because C++ is an extension of C it is possible for a C++ program to use stdio. Using stdio may be the easiest way for a C programmer to get started with C++, but using stdio is not a good style for C++ I/O. Its main drawbacks are its type insecurity and the inability to extend it consistently for user defined classes.

This document consists mainly of examples of the use of parts of the iostream library. It assumes a reasonable familiarity with C++, including such extensions to C as references, operator overloading, and the like. An attempt has been made to create examples that not only illustrate features of the iostream library, but represent good programming style. A programmer who is new to C++ may copy the examples "cookbook style," but cannot be said to have mastered C++ until he or she understands the examples.

Some of the examples are moderately complicated and demonstrate advanced features of the iostream library. These are included so that the document will continue to be useful as an aid even after the programmer has written a few programs using iostreams. The author is annoyed by "tutorials" that show how to do simple things that he could figure out himself, but are silent about the harder, more sophisticated kinds of code that he frequently wants to write.

This document is not a complete description of the iostream library. Some classes and members are not described at all. Some are used without complete descriptions. The reader is referred to the iostream man pages for more details.

The declarations for the iostream library exist in several header files. To use any part of it, a program should include `iostream.h`. Other header files may be needed for other operations. These are mentioned below, but the `#include` lines are never put in the examples.

The iostream library is divided into two levels. The low level (based on the `streambuf` class) is responsible for producing and consuming characters. This level is an independent abstraction and may be used without the upper level. This is appropriate when the program is moving characters around without much (or any) formatting operations.

The upper level is responsible for formatting. There are three significant classes. `istream` and `ostream` are responsible for input and output formatting, respectively. They are both derived from class `ios`, which contains members relating to error conditions and the interface to the low level. A third class, `iostream`, is derived (multiple inheritance) from both `istream` and `ostream`. It plays only a minor role in the library. A "stream class" is any class derived from `istream` or `ostream`.

The topics covered in this document are:

- Output — predefined output conversions, ways to deal with errors, and ways to adapt the library for output of user classes.
- Input — predefined input conversions, and ways to adapt the library for input of user classes.
- Constructing specialized streams — file I/O and incore operations.
- Format Control — An `ios` contains some format state variables. This section describes how they are manipulated by user code and interpreted by the predefined operations
- Manipulators — A powerful method for customizing operations.
- `streambufs` — How to use the low level interface.
- Deriving Streambuf Classes — Methods for creating specialized classes that specialize `streambuf` to deal with alternate producers and consumers of characters.
- Extending Streams — Deriving classes from `istream` and `ostream`, adding state variables, and initialization issues.
- Comparison of I/O libraries.
- Compatibility — Converting a program that uses the old stream library to use the new library.

Output

Suppose we want to print the variable `x`. The main mechanism for doing output in the iostream library is the *insertion* operator `<<`. This operator is usually called left shift (because that is its built-in meaning for integers) but in the context of iostreams it is called insertion.

```
cout << x ;
```

`cout` is a predefined `ostream` and if `x` has a numeric type (other than `char` or `unsigned char`) the insertion operator will convert `x` to a sequence of digits and punctuation, and send this sequence to standard output. There are different operations depending on the type of `x`, and the mechanism used to select the operator is ordinary overload resolution. The insertion operator for type `t` is called the "`t` inserter."

If we have two values we might do:

```
cout << x << y ;
```

which will output x and y, but without any separation between them. To annotate the output we might do:

```
cout << "x=" << x
     << ",y=" << y
     << ",sum=" << (x + y) << "\n" ;
```

This will not only print the values of x, y, and their sum, but labels as well. It uses the string (char*) inserter, which copies zero terminated strings to an ostream.

Notice the parentheses around the sum. These are not needed because the precedence of + is higher than that of <<. But, when using << as insertion, it is easy to forget that C++ is giving it a precedence appropriate to shift. Getting in the habit of always putting in parentheses is a good way to avoid nasty surprises such as having cout<<x&y output x rather than x&y.

The output might look like:

```
x=23,y=159,sum=182
```

A pointer (void*) inserter is also defined.

```
int x = 99 ;
cout << &x ;
```

It prints the pointer in hex.

A char inserter is defined:

```
char a = 'a' ;
cout << a << '\n' ;
```

This prints a and newline.

User Defined Insertion Operators

What if we want to insert a value of class type?

Inserters can be declared for classes and values of class type and used with exactly the same syntax as inserters for the primitive types. That is, assuming the proper declarations and definitions, the examples from the previous section can be used when x or y are variables with class types.

The simplest kinds of examples are provided by a struct that contains a few values.

```
struct Pair { int x ; int y ; } ;
```

We want to insert such values into an ostream, so we define:

```
ostream& operator<<(ostream& o, Pair p) {
        return o << p.x << " " << p.y ;
        }
```

This operator inserts two integral values (separated by a space) contained in `p` into `o`, and then returns a reference to `o`.

The pattern of taking an `ostream&` as its first argument and returning the same `ostream` is what makes it possible for insertions to be strung together conveniently.

As a slightly more elaborate example, consider the following class, which is assumed to implement a variable size vector:

```
class Vec {
private:
        ...
public:
                 Vec() ;
        int      size() ;
        void     resize(int) ;
        float&   operator[](int) ;
        ...
} ;
```

We imagine that `Vec` has a current `size`, which may be modified by `resize`, and that access to individual (float) elements of the vector is supplied by the subscript operator. We want to insert `Vec` values into an `ostream`, so we declare:

```
ostream& operator<< (ostream& o, const Vec& v) ;
```

The definition of this operator is given below. Using `Vec&` rather than `Vec` as the type of the second argument avoids some unnecessary copying, which in this case might be expensive. Of course, using `Vec*` would have a similar advantage in terms of performance, but would obscure the fact that it is the value of the `Vec` itself that is being output, and not the pointer.

The definition might be:

```
ostream& operator<< (ostream& o, const Vec& v)
{
        o << "[" ;        // prefix
        for ( int x = 0 ; x < v.size() ; ++x )
                // use comma as separator
                if ( x!=0 ) o << ',' ;
                o << v[x] ;
                }
        return o << "]" ;// suffix
        }
```

This will output the list as a comma separated list of numbers surrounded by brackets. The code takes care to get the empty list right and to avoid a trailing comma.

Propagating Errors

None of the examples so far has checked for errors. Omitting such checks would be bad style, except that the iostream library is arranged so that errors are propagated.

Streams have an error state. When an error occurs bits are set in the state according to the general category of the error. By convention, inserters ignore attempts to insert things into an `ostream` with error bits set, and such attempts do not change the stream's state. The error bits are declared in an enum, which is declared inside the declaration of class `ios`.

```
class ios {
        enum io_state { goodbit=0, eofbit=1, failbit=2, badbit=4 } ;
        } ;
```

`ios::goodbit` is not really a "bit." It is zero and indicates the absence of any bit.

In the definitions of the `Pair` and `Vec` inserters, if an error occurs some wasted computation may be done as the code does insertions that have no effect. But eventually the error will be properly propagated to the caller.

It is a good idea to check the output stream in some central place. For example:

```
if (!cout) error("aborting because of output error") ;
```

The state of `cout` is examined with `operator!`, which will have a non-zero value if the state indicates an error has occurred. This and other examples in this document assume that `error()` is a function to be called when an error is discovered, and that it does not return. But `error()` is not part of the iostream library.

An `ostream` can also appear in a "boolean" position and be tested.

```
if ( cout << x ) return ;
... ;           // error handling
```

The magic here is that `ios` contains a definition for `operator void*` that returns a non-null value when the error state is non-zero.

An explicit member function also exists:

```
if ( ... , cout.good() ) return ;
... ;           // error handling
```

The reader is referred to the man pages for other member functions that examine the error state.

Flushing

In many circumstances the iostream library accumulates characters so that it can send them to the ultimate output consumer in larger (presumably more efficient) chunks. This is a problem mainly in interactive programs where the user may need to see the output before entering input. It can also be a problem during debugging when the programmer may need to see how far the program has gotten before dumping core. The easiest way to make sure that everything inserted into an ostream has been sent to the ultimate consumer is to insert a special value, flush. For example:

```
cout << "Please enter date:" << flush ;
```

Inserting flush into an ostream forces all characters that have been previously inserted to be sent to the ultimate consumer of the ostream. flush is an example of a kind of object known as a *manipulator*, a value that may be inserted into an ostream to have some effect. It is really a function that takes an ostream& argument and returns its argument after performing some actions on it.

Another useful way to cause flushing is the endl manipulator, which inserts a newline and then flushes.

```
cout << "x=" << x << endl ;
```

Binary Output

Sometimes a program needs to output binary data or a single character.

```
int c='A' ;
cout.put(c) ;
cout << (char)c ;
```

The last two lines are equivalent. Each inserts a single character (A) into cout.

If we want to output a larger object in its binary form a loop using put would be possible, but a more efficient method is to use the write member. For example:

```
cout.write((char*)&x, sizeof(x))
```

will output the raw binary form of x.

The reader should notice that the above example violates C++ type discipline by converting &x to char*. Sometimes this is harmless, but if the type of x is a class with virtual member functions, or one that requires non-trivial constructor actions, the value written by the above cannot be read back in properly.

Input

Iostream input is similar to output. It uses extraction (>>) operators that can be strung together. For example:

```
cin >> x >> y ;
```

inputs two values from the predefined istream cin, which is by default the standard input. The extractor used will be appropriate for the types. The lexical details of numbers are discussed below under "Format Control." Whitespace characters (spaces, newlines, tabs, form-feeds) will be ignored before x and between x and y. For most types (including all the numeric ones), at least one whitespace character is required between x and y to mark where x ends.

There is a char extractor. For example:

```
char c ;
cin >> c ;
```

skips whitespace, extracts the next visible character from the istream and stores it in `c`. ("Non-whitespace" is too ugly a phrase for extensive use. This document uses "visible" instead. Strictly speaking this terminology is incorrect. For example, it classifies control characters as visible. But the term is reasonably euphonious and reasonably clear.)

Sometimes it is desirable to extract the next character unconditionally. For example:

```
char c ;
cin.get(c) ;
```

The next character is extracted and stored in `c`, whether or not it is whitespace.

User Defined Extraction Operators

Creating extractors for classes is similar to creating inserters. The `Pair` extractor could be defined thus:

```
istream& operator>>(istream& i, Pair& pair)
{
        return i >> pair.x >> pair.y ;
        }
```

By convention, an extractor converts characters from its first (`istream&`) argument, stores the result in its second (reference) argument, and returns its first argument. Making the second argument a reference is essential because the purpose of an extractor is to store a new value in the second argument.

A subtle point is the propagation of errors by extractors. By convention, an extractor whose first argument has a non-zero error state will not extract any more characters from the `istream` and will not clear bits in the error state, but it is allowed to set previously unset error bits. Further, an extractor that fails for some reason must set at least one error bit. The code in the `Pair` extractor does nothing explicitly to respect these conventions, but because the only way it modifies `i` is with extractors that honor the conventions, the conventions will be respected.

Conventions also apply to the meaning of the individual error bits. In particular `ios::failbit` indicates that some problem was encountered while getting characters from the ultimate producer, while `ios::badbit` means that the characters read from the stream did not conform to the expectation of the extractor. For example, suppose that the components of a `Pair` are supposed to be non-zero. The above definition might become:

```
istream& operator>>(istream& i, Pair& pair)
{
        i >> pair.x >> pair.y ;
        if ( !i ) return i ;
        if ( pair.x == 0 || pair.y == 0 ) {
                i.clear(ios::badbit|i->rdstate()) ;
                }
        return i ;
        }
```

This uses the (misleadingly named) `clear()` member function to set the error state to indicate that the extractor found incorrect data. Oring `ios::badbit` with `i->rdstate()` (the current state) preserves any bits that may previously have been set.

The `Pair` extractor has been defined so that it can input values that were output by the `Pair` inserter. Maintaining this symmetry is an important general principle that is worth some effort.

The next example is the `Vec` extractor, which will require an opening `[` followed by a sequence of numbers, followed by a `]`. Recall that the `Vec` inserter uses `,` as a separator and does not insert any whitespace between numbers. The extractor must accept such input. It will also accept slightly more general formats. In particular it allows extra whitespace, and it allows any visible character to be used as a separator. It also deals properly with a variety of special conditions such as errors in the input format.

```
istream& operator>>(iostream& i, Vec& v)
{
        int n = 0 ;             // number of elements
        char delim ;

        v.resize(n) ;

        // verify opening prefix
        i >> delim ;
        if ( delim != '[' ) ;
                i.putback(delim);
                i.clear(ios::badbit|i.rdstate()) ;
                return i ;
                }

        if ( i.flags() & ios::skipws ) i >> ws ;
        if ( i.peek() == ']' ) return i ;

        // loop
        while ( i && delim != ']' ) {
                v.resize(++n) ;
                i >> v[n-1] >> delim ;
                }

        return i ;
        }
```

The steps this code performs are:

- Turn `v` into an empty vector. This is done by the first `resize` operation.
- Verify that the next character in the istream is `[`.

  If the next character is not `[` (or if the state of the iostream already has error bits set), mark the state of `i` as bad, put `delim` back in `e` (where it may later be extracted again), and return. Putting `delim` back in the stream is not essential but it is consistent with the behavior of the predefined extractors.
- Optionally skip some whitespace.

  Whether to skip is controlled by the `ios::skipws` flag set in a collection of bits known as `i`'s format flags. This bit also controls skipping of whitespace in the predefined extractors. If it is set, whitespace was skipped before extracting the character stored into `delim`.
- If the next character is `]`, the input represents an empty vector and since `v` has already been resized the extractor can just return.

  The next character is examined using the `peek()` member function. This returns the next character that would be extracted but leaves it in the stream.

- The code now loops, extracting numbers and delimiters until either the closing `]` is found or an input error occurs. An explicit check of the state of `i` is required to prevent an infinite loop should an error occur in extracting `vec[n-1]` or `delim`.

`char*` Extractor

A useful extractor, but one that must be used with caution, takes a `char*` second argument. For example,

```
char p[100];
cin >> p;
```

skips whitespace on `cin`, extracts visible characters from `cin` and copies them into `p` until another whitespace character is encountered. Finally it stores a terminating null (0) character. The `char*` extractor must be used with caution because if there are too many visible characters in the `istream`, the array will overflow.

The above example is more carefully written as:

```
char p[100] ;
cin.width(sizeof(p)) ;
cin >> p ;
```

There are very few circumstances (perhaps there are none at all) in which it is appropriate to use the `char*` extractor without setting the "width" of the `istream`.

To make specifying a width more convenient, the `setw` manipulator (declared in `iomanip.h`) may be used. The above example is equivalent to:

```
char p[100] ;
cin >> setw(sizeof(p)) >> p ;
```

Binary Input

The `char` extractor skips whitespace. Programs frequently need to read the next character whether or not it is whitespace. This can be done with the `get()` member function. For example,

```
char c;
cin.get(c);
```

`get()` returns the `istream` and a common idiom is:

```
char c ;
while ( cin.get(c) ) {
        ...
        }
```

Programs also occasionally need to read binary values (e.g., those written with `write()`) and this can be done with the `read()` member function.

```
cin.read((char*)&x,sizeof(x)) ;
```

This does the inverse of the earlier `write` example (namely, it inputs the raw binary form of `x`).

If a program is doing a lot of character binary input, it may be more efficient to use the lower level part of the iostream library (`streambuf` classes) directly rather than through streams.

Creating Streams

The examples so far have used the predefined streams, `cin` and `cout`. For some programs, reading from standard input and writing to standard output suffices. But other programs need to create streams with alternate sources and sinks for characters. This section discusses the various kinds of streams that are available in the iostream library.

Files

The classes `ofstream` and `ifstream` are derived from `ostream` and `istream` and inherit the insertion and extraction operations respectively. In addition they contain members and constructors that deal with files. The examples in this section assume that the header file `fstream.h` has been included.

If the program wants to read or write a particular file it can do so by declaring an `ifstream` or `ofstream` respectively. For example,

```
ifstream  source("from") ;
if ( !source ) error("unable to open 'from' for input");
ofstream  target("to") ;
if ( !target ) error("unable to open 'to' for output");
char c ;
while ( target && source.get(c) ) target.put(c) ;
```

copies the file `from` to the file `to`. If the `ifstream()` or `ofstream()` constructor is unable to open a file in the requested mode it indicates this in the error state of the stream.

In some circumstances a program may wish to declare a file stream without specifying a file. This may be done and the filename supplied later. For example:

```
ifstream file ;
... ;
file.open(argv[1]) ;
```

It is even possible to reuse the same variable by closing it between calls to `open()`. For example:

```
ifstream infile ;
for ( char** f = &argv[1] ; *f ; ++f ) {
        infile.open(*f) ;
        ... ;
        infile.close() ;
        }
```

In some circumstances the program may already have a file descriptor (such as the integer 0 for standard input) and want to use a file stream. For example,

```
ifstream infile ;
if ( strcmp(argv[1],"-") ) infile.open(argv[1],input) ;
else                       infile.attach(0) ;
```

opens `infile` to read a file named by `argv[1]`, unless the name is `-`. In that case it will connect `infile` with the standard input (file descriptor 0). A subtle point is that closing a file stream (either explicitly or implicitly in the destructor) will close the underlying file descriptor if it was opened with a filename, but not if it was supplied with `attach`.

Sometimes the program wants to modify the way in which the file is opened or used. For example, in some cases it is desirable that writes append to the end of a file rather than rewriting the previous values. The file stream constructors take a second argument that allows such variations to be specified. For example,

```
ofstream outfile("out",ios::app|ios::nocreate) ;
```

declares `outfile` and attempts to attach it to a file named `out`. Because `ios::app` is specified all writes will append to the file. Because `ios::nocreate` is specified the file will not be created. That is, the open will fail (indicated in `outfile`'s error status) if the file does not previously exist. The enum `open_mode` is declared in `ios`.

```
class ios {
        enum open_mode { in, out, app, ate, nocreate, noreplace } ;
};
```

These modes are each individual bits and may be or'ed together. Their detailed meanings are described in the man pages.

Sometimes it is desirable to use the same file for both input and output. `fstream` is an `iostream` (a class derived via multiple inheritance from both `istream` and `ostream`). The type `streampos` is used for positions in an iostream. For example,

```
fstream tmp("tmp",ios::in|ios::out) ;
...
streampos p = tmp.tellp() ;// tellp() returns current position
tmp << x ;
...
tmp.seekg(p) ;     // seekg() repositions iostream
tmp >> x ;
```

saves the position of the file in `p`, writes `x` to it, and later returns to the same position to restore the value of x.

A variant of seekg() takes a streamoff (integral value) and a seek_dir to specify relative positioning. For example,

```
tmp.seekg(-10,ios::end) ;
```

positions the file 10 bytes from the end, and

```
tmp.seekg(10,ios::cur) ;
```

moves the file forward 10 bytes.

Incore Formatting

Despite its name, the iostream library may be used in situations that do not involve input or output. In particular, it can be used for "incore formatting" operations in arrays of characters. These operations are supported by the classes istrstream and ostrstream, which are derived from istream and ostream respectively. The examples of this section assume that the header file strstream.h has been included.

For example, to interpret the contents of the string argv[1] as an integer value, the code might look like:

```
int i ;
istrstream(argv[1]) >> i ;
```

The argument of the istrstream() constructor is a char pointer. In this example, there is no need for a named strstream. An anonymous constructor is more direct.

The inverse operation, taking a value and converting it to characters that are stored into an array, is also possible. For example,

```
char s[32] ;
ostrstream(s,sizeof(s)) << x << ends ;
```

will store the character representation of x in s with a terminating null character supplied by the ends (endstring) manipulator. The iostream library requires that a size be supplied to the constructor and nothing is ever stored outside the bounds of the supplied array. In this case, an "output error" will occur if an attempt is made to insert more than 32 characters.

In case it is inconvenient to preallocate enough space for the string, a program can use an ostrstream() constructor without any arguments. For example, suppose we want to read the entire contents of a file into memory.

```
ifstream in("infile") ;

// strstream with dynamic allocation
strstream incore ;

char c ;
while ( incore && in.get(c) ) incore.put(c) ;

// str returns pointer to allocated space
char* contents = incore.str() ;
...
// once str is called space belongs to caller
delete contents ;
```

The file `infile` is read and its contents inserted into `incore`. Space will be allocated using the ordinary C++ allocation (`operator new`) mechanism, and automatically increased as more characters are inserted. `incore.str()` returns a pointer to the currently allocated space and also "freezes" the `strstream` so that no more characters can be inserted. Until `incore` is frozen, it is the responsibility of the `strstream()` destructor to free any space that might have been allocated. But after the call to `str()`, the space becomes the caller's responsibility.

Predefined Streams

There are four predefined streams, `cin`, `cout`, `cerr`, and `clog`. The first three are connected to standard input, standard output, and standard error respectively. `clog` is also connected to standard error but, unlike `cerr`, `clog` is buffered. That is, characters are accumulated and written to standard error in chunks. `cout` is also buffered.

Frequently programs want to use either standard input and output or some external file depending on their command line arguments. One way is to use the predefined streams and assign to them. Assignment of streams is not possible in general but the predefined streams have special types which allow it. The reader is referred to the man pages for a discussion of the semantics of assignment. A more flexible style is to use a pointer or reference to a stream:

```
istream* in = &cin ;
...
if ( infile ) in = new ifstream(infile) ;
...
*in << x  ;
```

Problems can occur when mixing code that uses iostreams with code that uses stdio. There is no connection between the predefined iostreams and the stdio standard `FILE`s except that they use the same file descriptors. It is possible to eliminate this problem by calling

```
ios::sync_with_stdio()
```

which will connect the predefined iostreams with the corresponding stdio `FILE`s. Such connection is not the default because there is a significant performance penalty when the predefined files are made unbuffered as part of the connection.

Format Control

The default treatment of scalar types is that integral values (except `char` and `unsigned char`) are inserted in decimal, pointers (except `char*` and `unsigned char*`) in hex, floats and doubles with 6 digits of precision and all without leading or trailing padding. `char` and `unsigned char` values are just inserted as single characters. `char*` and `unsigned char*` values are treated as pointers to strings (null terminated sequences of characters). The default treatment for extraction of integer types is decimal numbers with leading whitespace permitted. An optional sign (+ or -) is permitted, but without whitespace between it and the digits. Extraction is terminated by a non-digit character. Extraction for floating point types is similar except that the lexical possibilities for floating point numbers are an optional sign followed (without intervening whitespace) by a number according to C++ lexical rules.

For many purposes these defaults are adequate. When they are not, the program can do more formatting itself, or it can use the format control features of the iostream library. The examples in this section use these features.

Associated with each iostream is a collection of "format state variables" that control the details of conversions. The most important of these is a `long int` value that is interpreted as a collection of bits. These bits are declared as:

```
enum    { skipws=01,            // skip whitespace on input
          left=02,  right=04, internal=010,
                                // padding location
          dec=020, oct=040, hex=0100,
                                // conversion base
          showbase=0200, showpoint=0400, uppercase=01000,
          showpos=02000,
                                // modifiers
          scientific=04000, fixed=010000
                                // floating point notation
          } ;
```

These may be examined and set individually or collectively. For example, the `ios::skipws` controls whether leading whitespace is skipped by extractors.

```
char c ;
cin.setf(0,ios::skipws) ;               // turn off skipping
cin >> c ;
cin.setf(ios::skipws,ios::skipws) ;     // turn it back on
```

The second argument of `setf` indicates which bits should be set. The first indicates what values they should be set to.

Manipulators are declared (in `iomanip.h`) that will have an equivalent effect. The above is equivalent to:

```
cin >> resetiosflags(ios::skipws)
    >> c
    >> setiosflags(ios::skipws) ;
```

`resetiosflags` resets (makes zero) the indicated bits and `setiosflags` sets (makes them 1) the indicated bits.

Commonly we want to save the flags (or other state variables) and restore their value later. Consider:

```
long f = cin.flags() ;
cin.setf(ios::skipws,ios::skipws) ;
cin >> c ;
cin.flags(f) ;
```

The variant of `flags` without an argument returns the current value. state variable The variant with an argument stores the argument into the `flags` state variable. This code does the same extraction as the previous code, but instead of arbitrarily leaving `cin` with skipping on it restores skipping to its previous status.

The pattern of member functions is repeated for other state variables. That is, if `svar` is some state variable, and `s` is a stream, then `s.svar()` returns the current value of the state variable and `s.svar(x)` stores the value `x` into the state variable.

Field Widths

The default behavior of the inserters is to insert only as many characters as is necessary to represent the value, but frequently programs want to have fixed size fields.

```
cout.width(5) ;
cout << x ;
```

will output extra space characters preceding the digits to bring the total number of inserted characters to five. If the value of `x` will not fit in five characters, enough characters will be inserted to express its value. The numeric inserters never truncate. The `width` state variable might be regarded as an implicit parameter of extractors because it is reset to 0 (which induces the default behavior) whenever it is used.

```
cout.width(5) ;
cout << x << " " << y ;
```

will output `x` in at least five characters, but will use only as many characters as necessary in outputting the separating space and `y`.

The value of the `width` state variable is honored by the inserters of the iostream library, but user defined inserters are responsible for interpreting it themselves. For example, the `Pair` inserter defined previously does nothing special with `width` and so if it is non-zero when the inserter is called the width will apply to the first `int` inserted, and not the second. If the inserter wants to honor `width` its definition might look like:

```
ostream& operator<<(ostream& o, Pair p) {
         int w = o.width() ;
         o.width(w/2) ;
         o << p.x << " " ;
         o.width(w/2-((w+1)&1)) ;
         o << p.y ;
         return o ;
         }
```

This inserts each number in half the requested width.

It is slightly awkward to mix calls to the `width()` member function with insertion operations. The manipulator `setw()` may be used. An alternative definition of the `Pair` inserter might be:

```
iostream& operator<<(iostream& ios, Pair p) {
         int w = ios.width() ;
         return ios << setw(w/2) << pair.x << " "
                  << setw(w/2+((w+1)&1)) << pair.y ;
         }
Pair
```

`width` is always interpreted as a minimum number of characters. There is no direct way to specify a maximum number of characters. In cases where a program wants to insert exactly a certain number of characters, it must do the work itself. For example,

```
if ( strlen(s) > w ) cout.write(s,w) ;
else                 cout << setw(w) << s ;
```

will always insert exactly `w` characters.

`width` is generally ignored by extractors, which tend to rely on the contents of the iostream to detect the end of a field. There is, however, an important exception. The `char*` extractor interprets a non-zero width to be the size of the array. For example,

```
char a[16] ;
cin >> setw(sizeof(a)) >> a ;
if ( !isspace(cin.peek() ) error("string too long") ;
```

protects the program in case there are sixteen or more visible characters. As a further measure of protection, the extractor stores a trailing null in the last byte of the array when it stops because there are too many visible characters. This means that the number of characters extracted (not counting leading whitespace) will be at most one less than the specified width.

Flags control whether padding (when it occurs) causes the field to be left or right justified. The `fill` state variable (whose initial value is a space) supplies the character to be inserted.

```
cout.fill(*) ;
cout.setf(ios::left,ios::adjustfield) ;
cout << setw(5) << 13 << "," ;
cout.fill(#) ;             // set state variable
cout.setf(ios::right,ios::adjustfield) ;
cout << setw(5) << 14 << "\n" ;
```

results in a line of output that looks like:

```
13***,###14
```

Conversion Base

Integers are normally inserted and extracted in decimal notation, but this is controlled by flag bits. If none of `ios::dec`, `ios::hex`, or `ios::oct` are set the insertion is done in decimal but extractions are interpreted according to the C++ lexical conventions for integral constants. If `ios::showbase` is set then insertions will convert to an external form that can be read according to these conventions.

For example,

```
int x = 64;
cout << dec << x << " "
     << hex << x << " "
     << oct << x << endl ;
cout.setf(ios::showbase,ios::showbase) ;
cout << dec << x << " "
     << hex << x << " "
     << oct << x << endl ;
```

will result in the lines:

```
64 40 100
64 0x40 0100
```

`setf()` with only one argument turns the specified bits on, but doesn't turn any bits off.

Reading the lines shown above could be done by:

```
cin >> dec >> x
    >> hex >> x
    >> oct >> x
    >> resetiosflags(ios::basefield)
    >> x >> x >> x ;
```

The value stored in `x` will be 64 for each extraction. The `resetiosflags()` manipulator turns off the specified bits in the flags.

Miscellaneous Formatting

As a precaution against looping, zero width fields are considered a bad format by the extractors. So if the next character is whitespace and ios::skipws is not set, the arithmetic extractors will set an error bit.

The number of significant digits inserted by the floating point (double) inserter is controlled by the precision state variable. The details of the conversion are further controlled by certain flags. The reader is referred to the man page for more details.

It is good practice to flush ostreams appropriately. The flush and endl manipulators make it relatively easy to do so. Yet, there are circumstances in which some automatic flushing is appropriate. This is supported by the ostream* valued state variable tie. If i.tie is non-null and an istream needs more characters, the ostream pointed at by tie is flushed. Initially cin is tied in this fashion to cout so that attempts to get more characters from standard input result in flushing standard output. This seems to handle most interactive programs reasonably well without imposing a large performance penalty on non-interactive programs and without creating different behavior when programs are connected to pipes rather than directly to a terminal. (Programs that won't work when their input or output is connected to a pipe are one of the author's pet peeves.) The overheads implied by tying are relatively small when compared with "big" extractors (such as the arithmetic ones) but may be large when single character operations are being performed. For this reason it is sometimes a good idea to break the tie by setting the state variable to 0. For example:

```
char c ;
// break the tie to improve performance of get.
cin.tie(0) ;
while ( cin.get(c) ) cout.put(c) ;
```

Manipulators

A manipulator is a value that can be inserted into or extracted from a stream to cause some special side effect. That is, some side effect besides inserting a representation of its value, or extracting characters and converting them to a value. A parameterized manipulator is a function (or a member of a class with an operator()) that returns a manipulator. Previous sections contain examples of the use of manipulators and parameterized manipulators. This section contains examples illustrating how to define manipulators. The predefined manipulators and macros discussed in this section are declared in the header file iomanip.h.

A (plain) manipulator is a function that takes an istream& or ostream& argument, operates on it in some way, and returns it. A (pointer to a) function of this type may be extracted from or inserted into a stream, respectively.

Many examples of manipulators (such as flush or endl) have already appeared in this paper. For example, a manipulator to insert a tab can be defined:

```
ostream& tab(ostream& o) {
        return o << '\t' ;
        }
...
cout << x << tab << y ;
```

This seems over elaborate. Why not simply define tab as a character or string? One possible reason has to do with the namespace. There can be only one (global) variable in a C++ program named `tab` but because of overloading there can be many functions with that name.

Another common use of manipulators is to shorten the long names and sequences of operations required by the iostream library. For example,

```
ostream& fld(ostream& o) {
        o.setf(ios::showbase,ios::showbase) ;
        o.setf(ios::oct, ios::basefield) ;
        o.width(10) ;
        return o ;
        }
...
cout << fld << x ;
```

It is common for the function that manipulates a stream to need an auxiliary argument. `setw()` is an example of such a parameterized manipulator. To use parameterized manipulators the program must include `iomanip.h`.

For example, we might want to supply the value to be printed to `fld` in the above.

```
ostream& fld(ostream& o, int n ) {
        long f = flags(ios::showbase|ios::oct) ;
        o << setw(10) << n ;
        flags(f) ;          // restore original flags
        return o ;
        }

OMANIP(int) fld(int n) {
        return OMANIP(int)(fld,n) ;
        }
...
cout << fld(23) ;
```

`OMANIP` is a macro and `OMANIP(int)` expands to the name of a class declared in `iomanip.h`. An `OMANIP(int)` insertion operator is also declared in `iomanip.h` and is used in the example. Note that `fld` in the above is overloaded; it is both the function that manipulates the stream and a function that returns an `OMANIP(int)`.

If we need parameterized manipulators for parameter types other than `int` and `long` (which are declared in `iomanip.h`), they must be declared. For example, suppose we want to read numbers that may have a suffix.

```
typedef long& Longref ;
IOMANIPdeclare(Longref) ;
        // Declares IMANIP(Longref), OMANIP(Longref), IOMANIP(Longref)
        //          IAPP(Longref), OAPP(Longref), IOAPP(Longref)

istream& in_k(istream& i, long& n)
{
        // Extract an integer.
        // If suffix is present multiply by 1024
        i >> n ;
        if ( i.peek() == 'k' ) {
                i.ignore(1) ;
                n *= 1024 ;
                }
        return i ;
        }

IAPP(Intref) in_k = in_k ;
        // IAPP(Intref) is the type of an Intref applicator
        // in_k on right is function, on left variable

...
long n ;
cin >> in_k(n) ;
```

The `IOMANIPdeclare(T)` declares manipulators (and applicators) for type `T`. Because of the way the macro `IOMANIPdeclare` expands, the argument must be an identifier. In this case a `typedef` is required to create manipulators for `long&`. An applicator is something that behaves like a function returning a manipulator. That is, it is a class with an `operator()` member.

Sometimes we want a manipulator with more than one parameter. One way to achieve this effect is to define a manipulator on a class. For example, a manipulator that can be used to repeat a string might look like:

```
cout << repeat("ab",3) << endl ;
```

to result in a line containing "ababab." A possible definition of repeat would be

```
struct Repeatpair {
        const char* s ;
        int n ;
} ;

IOMANIPdeclare(Repeatpair) ;

static ostream& repeat(ostream& o, Repeatpair p) {
        // insert p.s into o, p.n times
        for ( int n = p.n ; n > 0 ; --n ) o << p.s ;
        return o ;
        }

OMANIP(Repeatpair) repeat(const char* s, int n) {
        Repeatpair p ;
        p.s=s ; p.n=n ;
        return OMANIP(Repeatpair)(repeat,p) ;
        }
```

Manipulators are a powerful and flexible method of extending the default inserters and extractors.

The Sequence Abstraction

The iostream library is built in two layers: The formatting layer discussed in previous sections, and a sequence layer based on the class `streambuf`. The formatting layer is responsible for converting between sequences of characters and various types of values and for high level manipulations of the streams. The sequencing layer is responsible for producing and consuming those sequences of characters. The most common way of using streambufs is with a stream. But `streambuf` is an independent class and may be used directly.

Abstractly, a `streambuf` represents a sequence of characters and two pointers into that sequence, a `get` and a `put` pointer. These pointers should be thought of as pointing at the locations either before or after characters in the sequence, rather than at specific characters. The sequences and pointers may be manipulated in a variety of ways, with the two fundamental ones being fetching the character after the get pointer, and storing a character in the position after the put pointer. Storing either replaces any previous character at that location or, if the put pointer was at the end of the sequence, extends the sequence. Other manipulations may move the pointers in various ways.

For the examples of this section, we assume that there are two `streambufs`, pointed at by `in` and `out`. Methods for constructing `streambufs` appear later, but it is easy enough to get at the `streambuf` associated with a stream via `rdbuf()`. So we assume that `in` and `out` have been initialized with

```
streambuf* in = cin.rdbuf() ;
streambuf* out = cout.rdbuf() ;
```

An `istream` or `ostream` retains no information about the state of the associated `streambuf`. For example a program may alternate between extracting characters from `in` and `cin`.

The simplest operations are getting and putting characters. A simple loop to copy characters from one streambuf to another would be:

```
int c ;
while (( c = in->sbumpc()) != EOF ) {
         if ( out->sputc(c) == EOF ) error("output error") ;
         }
```

`sbumpc()` fetches the character after the get pointer and advances the get pointer over the fetched character. `sputc()` stores a character into the sequence and moves the put pointer past it. Both functions report errors by returning `EOF`, which is why `c` must be declared an `int` rather than a `char`. `EOF`s returned while fetching tend to mean that the streambuf has run out of characters from the ultimate producer. `EOF`s returned when storing tend to signal real errors. Because, unlike iostreams, streambufs do not contain any error state, it is possible that a store or fetch might fail one time and succeed the next time it is tried.

The `streambuf` class contains several different member functions for manipulating the get pointer. The following loop represents a common idiom:

```
int c = in->sgetc() ;
while ( c!=EOF && !isspace(c) ) {
         c = in->snextc() ;
         }
```

It scans the streambuf looking for a whitespace character (i.e., one for which `isspace` is non-zero). It stops when it finds that character leaving it available for extraction. This is because `sgetc()` and `snextc()` do not behave the way many programmers expect. `sgetc()` returns the character after the get pointer, but does not move the pointer. `snextc()` moves the get pointer and then returns the character that follows the new location. As usual both these functions return `EOF` to signal an error.

The copy loop moved characters one at a time. It is possible to do larger chunks, as in:

```
static const int Bufsize = 1024 ;
char buf[Bufsize] ;
int p, g ;
do {
         g = sgetn(buf, Bufsize) ;
         p = sputn(buf, g) ;
         if ( p!=g ) error("output error");
         } while ( g>0 ) ;
```

`sgetn(b,n)` attempts to fetch *n* characters from the sequence into the array starting at `b`. Similarly `sputn(b,n)` tries to store the *n* characters starting at `b` into the sequence. Both move the pointer (get or put respectively) over the characters they have processed and return the number transferred. For `sgetn()` this will be less than the number requested when the end of sequence is reached. When `sputn()` returns less than the number requested, it indicates an error of some sort.

Buffering Exposed

As the name suggests `streambufs` may implement the sequence abstraction by buffering between the source and sink of characters. This results in an unfortunate pun. The word "buffer" is frequently used informally to designate a `streambuf`, but it is also used to describe the chunking of characters. Thus, the oxymoron "unbuffered buffer" refers to a `streambuf` in which characters are passed to the ultimate consumer as soon as they are stored, and obtained from the ultimate producer whenever they are retrieved.

In light of the buffering provided by streambufs, the reader will not be surprised to discover that arrays of characters are used in the implementation. The `streambuf` class contains some member functions that make the presence of such arrays visible to the program. With some effort, they might be used to "break the abstraction," but the intended purpose is to deal with the delays implicit in buffering.

The earlier example using `sgetn()` and `sputn()` to copy from `in` to `out` waits until `Bufsize` characters become available (or the end of the sequence is reached) before passing any to `out`. If the source of characters has delays (e.g., it is a person typing at a terminal) and we want the characters to be passed on as soon as they become available; the program might use operations on single characters instead, or it might use an adaptive method such as:

```
static const int Bufsize = 1024 ;
char buf[Bufsize] ;
int p, g ;
do {
        in->sgetc() ;          // force a character in buffer
        g = in->in_avail() ;
        if ( g > Bufsize ) g = Bufsize ;
        g = in->sgetn(buf,g) ;
        p = out->sputn(buf,g) ;
        out->sync() ;
        if ( p!=g ) error("output error");
        } while ( g > 0 )
```

`in_avail` returns the number of characters immediately available in the array. Calling `sgetc()` first forces there to be at least one such character (unless the get pointer is at the end of the sequence). Recall that `sgetc()` returns the next character, but doesn't move the get pointer. The code calls `sync()` after it has put characters into `out`, thus causing these characters to be sent to the ultimate consumer.

In some circumstances, such as when streambufs are being used for interprocess messages, the chunks in which characters are produced and consumed may have significance. The above preserves these chunks provided they are less than `Bufsize` and they fit into the arrays of `in` and `out`. To ensure that this latter condition is met, the code should provide large enough arrays explicitly with:

```
char ibuf[Bufsize+8], obuf[Bufsize+8] ;
in->setbuf(ibuf,sizeof(ibuf)) ;
out->setbuf(obuf,sizeof(obuf)) ;
```

The calls to `setbuf()` should be done before any fetches or stores are done. The arrays are eight larger than required by the largest chunk to allow for various overheads. Of course, this code behaves properly only when `in` delivers the characters in the appropriate chunks.

Using Streambufs in Streams

The positions of the put pointer after operations that store characters and position of the get pointer after operations that fetch characters are well defined by the sequence abstraction. But the location of the get pointer after stores, and the location of the put pointer after fetches is not. Most specializations of `streambuf` (i.e., classes derived from it) follow one of two patterns. Either the class is queuelike, which means that the put pointer and the get pointer are independent and moving one has no effect on the other. Or the class is filelike, which means that when one pointer moves the other is adjusted to point to the same place. So a filelike class behaves as if there were only one pointer. Other possibilities are logically possible, but do not seem to be as useful.

A queuelike streambuf, may be shared between two streams. For example:

```
strstreambuf b ;
ostream ins(&b) ;
istream extr(&b) ;
while ( ... ) {
        ins << x ; ... ;
        extr >> x ;  ... ;
        }
```

This example explicitly uses the `strstreambuf` class (declared in `strstream.h`) which is also used (implicitly) by the `istrstream` and `ostrstream` classes. The `istream()` and `ostream()` constructors require a `streambuf` argument. They use that `streambuf` as a producer or consumer of characters. The characters inserted into `ins` may later be extracted from `extr`. If an attempt is ever made to extract more characters than have been inserted, the extraction will fail. If more characters are later inserted, `extr`'s error state can be cleared and the extraction retried.

Because of the dynamic allocation performed by `strstreambufs` the queue is unbounded, but there is a serious drawback. Space is not reclaimed until `b` is destroyed.

Deriving New Streambuf Classes

The `streambuf` class is intended to serve as a base class. Although it contains members to manipulate the sequences, it does not contain any mechanism for producing or consuming characters. These must be provided by a derived class. The iostream library contains several such derived streambuf classes, but a program may define new ones.

The members of a class that are intended for use by derived classes are `protected`, and the data structure as seen by a derived class is said to be the protected interface of the `streambuf` class. This abstraction exposes the details of the array management that is implicit in the buffering provided by streambufs. It consists of two parts. The first part is member functions of `streambuf` that permit access to and manipulation of the arrays and pointers used to implement the sequence abstraction. The second part is virtual members of `streambuf` that must be supplied by the derived class.

The principle example of this section will be the implementation of `fctbuf`, whose declaration looks like:

```
typedef int (*action)(char* b, int n, open_mode m) ;

class fctbuf : public streambuf {
public:
         fctbuf(action f,open_mode m) ;
private: ...
} ;
```

When called with `m=ios::out`, an `action()` function processes the `n` characters starting at `b`. When called with `m=ios::in`, it stores `n` characters starting at `b`. It returns non-zero to indicate success and zero to indicate failure.

The declaration of `fctbuf` looks like:

```
class fctbuf : public streambuf {
public:                             // constructor
         fctbuf(action a, open_mode m) ;

private:                            // data members
         action   fct ;
         open_mode
                  mode ;
         char     small[1] ;

protected:                          // virtuals
         int      overflow(int) ;
         int      underflow() ;
         streambuf*
                  setbuf(char*,int,int) ;
         int      sync() ;

} ;
```

The constructor just initializes the data elements. The action function `a` will be called only in modes compatible with `m`.

```
fctbuf::fctbuf(action a, open_mode m)
         : fct(a), mode(m) { }
```

The virtual functions define details that make `fctbuf()` behave properly. The `streambuf` protected interface is organized around three areas (`char` arrays), the holding area, the get area, and the put area. Characters are stored into the put area and fetched from the get area.

As characters are stored in the put area, it shrinks until there is no more space available. If an attempt is made to store a character when the put area has no space, a new area must be established. Before that can be done the old characters must be consumed. Both these tasks are the responsibility of the `overflow()` function. Similarly, the get area is shrunk by fetches and is eventually empty. If more characters are needed the `underflow()` function must create a new get area. Both `overflow()` and `underflow()` will use the holding area to initialize the put or get area (respectively).

setbuf

The virtual function `setbuf` is called by user code to offer an array for use as a holding area. It can also be used to turn off buffering.

```
streambuf* fctbuf::setbuf(char* b, int len)
{
         if ( base() ) return 0 ;

         if ( b!=0 && len > sizeof(small) ) {
                  // set up holding area
                  setb(b,b+len) ;
                  }
         else {
                  // Use a one character array to achieve
                  // "unbuffered" actions.
                  setb(small,small+sizeof(small)) ;
                  }
         setp(0,0) ;               // put area
         setg(0,0,0) ;             // get area
         return this ;
         }
```

The actions of this function are:

- `base()` points to the first character of the holding area. If a holding area has already been set up (`base` non-zero) a new one cannot be established and `setbuf()` returns a null pointer as an error indication.
- If an array is supplied and is sufficiently large, `setb()` is called to set up the pointers to the holding area. Its first argument becomes `base`, the first `char` of the holding area, and its second becomes `ebuf`, the `char` after the last. Otherwise the `fctbuf` will become unbuffered. This is noted by setting up a one character holding area.
- Finally the pointers related to the put area are set to 0 by `setp()` and the pointers related to the get area are set to 0 by `setg()`.

overflow

The virtual function `overflow()` is called to send some characters to the consumer, and establish the put area. Usually (but not always) when it is called, the put area has no space remaining.

```
int fctbuf::overflow(int c) {
        // check that output is allowed
        if ( !(mode&ios::out) ) return EOF ;

        // Make sure there is a holding area
        if (  allocate()==EOF ) return EOF ;

        // Verify that there are no characters in
        // get area.
        if ( gptr() && gptr() < egptr() ) return EOF ;

        // Reset get area
        setg(0,0,0) ;

        // Make sure there is a put area
        if ( !pptr() ) setp(base(),base()) ;

        // Determine how many characters have been
        // inserted but not consumed.
        int w = pptr()-pbase() ;

        // If c is not EOF it is a character that must
        // also be consumed.
        if ( c != EOF ) {
                // We always leave space
                *pptr() = c ;
                ++w ;
                }

        // consume characters.
        int ok = (*fct)(pbase(), w, ios::out) ;

        if ( ok ) {
                // Set up put area.  Be sure that there
                // is space at end for one extra character.
                setp(base(),ebuf()-1) ;
                return zapeof(c) ;
                }
        else {
                // Indicate error.
                setp(0,0) ;
                return EOF ;
```

```
                    }
            }
```

Some explanations of this code:

- It first tests for various error conditions, such as trying to do insertion when there are characters that have been produced but not extracted. This is a problem because the code only uses one area to hold characters for insertion and extraction. It would also be possible to ignore this condition and just throw away the characters or a more elaborate version of `fctbuf` might use separate areas for insertion and extraction.
- `allocate()` is a part of the `streambuf` protected interface. If no reserve area has previously been specified it allocates heap space.
- `pbase` is the value of `pptr` established by the last call to `setp()`. As characters are stored, `pptr` is moved so that it always points to the first unused character. Thus the characters between `pbase` and `pptr` have been stored and not consumed. They are now sent to the consumer.
- The value returned by the consumer is checked to verify that it has been able to consume all the characters that were passed to it. If not, there is no put area and `EOF` is returned.
- When all has gone well the put area is established by `setp()` whose first argument becomes `pptr` (pointing to the first `char` of the put area) and whose second becomes `epptr` (pointing to the `char` after the last `char` of the put area). In this case when no errors have occurred the whole holding area minus the last character is used as a put area. The last character will usually be filled in by the character supplied to the next call to `overflow()`.
- Finally, if all has gone well, `c` is returned unless it is `EOF`. If `c` is `EOF` something else must be returned because `EOF` is returned to signal an error. The macro `zapeof()` deals with this contingency.

underflow

The underflow function is called when characters are needed for fetching and none are available in the get area. Its general outline is similar to `overflow()`, but it deals with the get area rather than the put area.

```
int fctbuf::underflow() {
        // Check that input is allowed
        if ( !(mode&ios::in) ) return EOF ;

        // Make sure there is a holding area.
        if (allocate()==EOF) return EOF ;

        // If there are characters waiting for output
        // send them ;
        if ( pptr() && pptr() > pbase() ) overflow(EOF) ;

        // Reset put area
        setp(0,0) ;

        // Setup get area ;
        if ( blen() > 1 ) setg(base(),base()+1,ebuf()) ;
        else              setg(base(),base(),ebuf()) ;

        // Produce characters
        int ok = (*fct)(base(),blen(),ios::in) ;

        if ( ok ) {
                return zapeof(*base()) ;
                }
        else {
                setg(0,0,0) ;
                return EOF ;
                }
        }
```

Some explanations:

- EOF is returned immediately if we aren't supposed to do input or if a holding area cannot be allocated.
- allocate() is called to make sure that there is a holding area.
- setg() is used to establish the get area where fct will be asked to store characters. Its first argument sets up a pointer, eback, that marks the limit to which putback can move gptr. The second argument becomes gptr, and the last becomes egptr, pointing at the char after the last char containing values stored by the producer.
- blen() returns the size of the holding area. It may be as small as 1.
- If the action function indicated success underflow() returns the first character. It is left in the get area and may be extracted again. zapeof() is used to make sure that the returned result is not EOF. If zapeof() were omitted this might occur on a machine in which chars are signed and EOF is -1.

sync

The virtual function `sync()` is called to maintain synchronization between the various areas and the producer or consumer. It is also called by the `streambuf()` destructor.

```
int fctbuf::sync()
{
        if ( gptr() && egptr() > gptr() ) {
                // no way to return characters to producer
                return EOF ;
                }

        if ( pptr() && pptr() > pbase() ) {
                // Flush waiting output
                return overflow(EOF) ;
                }

        // nothing to do
        return 0 ;
        }
```

The virtual functions defined above implement a correct `streambuf` class. A possible refinement would be to provide implementations of the virtual `xsputn()` and `xsgetn()` functions. These functions are called when chunks of characters are being inserted and extracted respectively. Their default actions are to copy the data into the buffer. If they were defined in the `fctbuf` class they could call the functions directly and avoid the extra copy.

Extending Streams

There are two kinds of reasons to extend the basic stream classes. The first is to specialize to a particular kind of `streambuf` and the second is to add some new state variables.

Specializing `istream` or `ostream`

When the iostream library is specialized for a new source or sink of characters the natural pattern is this: First derive a class from `streambuf`, such as `fctbuf` in the previous section. Then derive classes from whichever of `istream`, `ostream`, or `iostream` is appropriate. For example, suppose we want to do this with the `fctbuf` class defined in the previous section. The streams might get the definitions:

```
class fctbase : virtual public ios {
public:
                  fctbase(action a, open_mode m)
                           : buf(a,m) { init(&buf) ; }
private:
         fctbuf   buf ;
} ;

class ifctstream : public fctbase, public istream {
public:
                  ifctbase(action a)
                           : fctbase(a, ios::in) { }
} ;

class ofctstream : public fctbase, public ostream {
public:
                  ofctbase(action a)
                           : fctbase(a, ios::out) { }
} ;

class iofctstream : public fctbase, public iostream {
public:
                  iofctstream(action a open_mode m)
                           : fctbase(a, m) { }
} ;
```

Derivations from ios are virtual so that when the class hierarchy joins (as it does in iofctstream) there will be only one copy of the error state information. Because the derivation from ios is virtual an argument cannot be supplied to its constructor. The streambuf is supplied via ios::init(), which is a protected member of ios intended precisely for this purpose.

Extending State Variables

In many circumstances we would like to add state variables to streams. For example, suppose we are printing trees and would like to have an indentation level associated with an ostream.

```
int xdent = ios::xalloc() ;
        // generate a unique index

ostream& indent(ostream& o) {
        // manipulator that inserts newlines and
        // appropriate number of tabs
        o << '\n' ;
        int count = o.iword(xdent) ;
        while ( count-- > 0 ) o << '\t' ;
        return o ;
        }

ostream& redent(ostream& o, int n) {
        // parameterized manipulator that modifies
        // indentation level
        o.iword(xdent) += n ;
        }

OAPP(int) redent = redent ;
```

`o.iword(xdent)` is a reference to the `xdent`'th integer state variable. Each call to `ios::xalloc` returns a different index. The index may then be used to access a word associated with the stream. The reason for calling `ios::xalloc` to get an index rather than just picking an arbitrary one is that it allows combining code that uses the indentation level with code that may have extended the formatting state variables for some other purpose.

A subtle problem occurs in the above example because `xdent` is initialized by a function call. What if `indent()` or `redent()` were called before `xdent` was initialized? Can that happen? Yes it can. It can happen if `indent()` or `redent()` is called from inside a constructor that is itself called to initialize some variable with program extent. Problems with order of initialization when doing I/O in constructors are common. The solution relies on "tricks" to force initialization order. In this case we would put into the header file containing the declarations of `indent()` and `redent()`:

```
static class Indent_init {
        static int count ;
public:
                Indent_init() ;
                ~Indent_init() ;
} indent_init ;
```

Each file that includes this header file will have a local variable `indent_init` that has to be initialized. Because this variable is declared in the header its initialization will occur early.

The definition of the constructor and destructor looks like:

```
static Iostream_init* io ;

Indent_init::Indent_init()
{
         // count keeps track of the difference between how
         // many constructor and destructor calls there are
         if ( count++ > 0 ) return ;

         // This code is executed only the first time
         io = new Iostream_init ;
         xdent = ios::xalloc() ;
         }

Indent_init::~Indent_init()
{
         if ( --count ) > 0 ) return ;

         // This code will be executed the last time
         delete io ;
         }
```

The iostream library uses this idea itself. The constructor for `Iostream_init` causes the iostream library to be initialized the first time it is called. It also keeps track of how many times the constructor is called and will do finalization operations on various data structures the last time it is called. It is therefore important that any values of type `Iostream_init` that are constructed by a program are eventually deleted. This is the purpose of having an `Indent_init` destructor; even though there are no finalization operations associated with indentation, it must delete `io`.

Comparison of Iostreams, Streams, and Stdio

The stdio library served C programmers well for many years. However, it has several deficiencies:

- The use of functions, like `printf()`, that accept variable numbers and types of arguments mean that type checking is subverted at an important point in many programs.
- There is no mechanism for extending it to user defined classes. The only way to add new format specifiers to `printf()` is to reimplement it.
- The mechanism is closely tied to file I/O. `sprintf()` explicitly extends it to incore operations, but there is no general method for creating alternate sources and sinks of data.

After stdio, the next stage of development was the stream library. Its most significant innovation was the introduction of insertion and extraction operations. The first two problems with stdio were elegantly solved. It was in use by C++ programmers for several years. But the stream library had problems of its own:

- The mechanism for creating sources and sinks of characters (`streambuf` class) was not documented or designed for extension.
- The full range of UNIX file operations was not supported. In particular there were no repositioning operations (`seeks`).
- There was only limited control over formatting. Programs frequently reverted to `printf()` like functions to specify alternative formats for numbers. A fixed size area was allocated for converting values to strings and then outputting the strings. Although it was not a problem in practice, in theory this buffer was subject to overflows.

The iostream library presented in this document has resolved these problems. It is relatively new, and whether significant problems will emerge in the future is not yet known. Some apparent deficiencies are:

- There is no way to determine if a producer has characters available, and no way to select input from one of multiple sources. This is, of course, also a deficiency of stdio and streams.
- There is no way to process data in the buffers without copying them out. This extra copying step can be expensive when simple operations (e.g., scanning for a specific character) are being performed.
- Some formatting operations tend to be wordier than the equivalent stdio operations. This is compensated for by the ability to define manipulators and inserters.

Converting from Streams to Iostreams

The iostream library is mostly upward compatible with the older stream library, but there are a few places where differences may affect programs. This section discusses those differences.

The major conceptual difference is that in the iostream library, `streams` and `streambufs` are regarded solely as abstract classes. The old stream classes provided certain specialized behaviors, specifically incore formatting and file I/O. In the iostream library these are supported solely through derived classes.

The old stream library declared everything in the header file `stream.h`. The iostream library uses `iostream.h` and some other headers. For compatibility a `stream.h` is supplied that includes `iostream.h` and other headers that are required for compatibility and defines a variety of items whose names are different in the iostream and stream libraries.

`streambuf` Internals

The internals of the `streambuf` class in the stream library were all public. Any program that relies on these internals will break because they are different (and private) in the iostream library.

How to derive new `streambuf` classes was not documented in the stream library. But it is such a natural idea to do so that many programs do it. Converting these programs to the iostream library may require changes in the derived `overflow()` and `underflow()` functions. The functionality of these functions in the iostream library is essentially the same as in the stream library. But because the internals of `streambuf` have changed, some code changes will probably be required. In particular the code will have to use the (protected) `streambuf` member functions `setb()`, `setg()`, and `setp()` instead of directly manipulating the pointers.

Incore Formatting

In the stream library the use of arrays of characters as sources or sinks was supported as the default behavior of `streambuf`. Although some attempt to preserve the default behavior is made by the iostream library these uses of a `streambuf` are considered obsolete. The support of incore operations is specifically the responsibility of the `strstreambuf` declared in `strstream.h`. `streambufs` created for this purpose can usually be replaced directly by `strstreambufs` that have equivalent behavior. The stream usage:

```
char* buf[10] ;
streambuf b(buf,10) ;
```

is equivalent to the iostream:

```
char* buf[10] ;
strstreambuf b(buf,10) ;
```

and the old method for initializing a streambuf for extraction:

```
char* buf[10] ;
streambuf b ;
b.setbuf(buf,10,buf+5) ;
```

is equivalent to the iostream method:

```
char* buf[10] ;
strstreambuf b(buf,10,buf+5) ;
```

Frequently these uses of `streambuf` do not appear explicitly in the program but are the consequence of using certain constructors of `istream` and `ostream`. These constructors are supplied in the iostream library, but are considered obsolete. The equivalent forms using `strstream` should be used.

The old method of storing a formatted value into an array:

```
char* buf[10] ;
ostream out(10,b) ;
```

is replaced by:

```
char* buf[10] ;
ostrstream out(b,10) ;
```

Note that the order of the arguments is reversed. The new order creates more consistency between various uses of strstreams.

The old method of extracting a formatted value from an array:

```
char* buf[10] ;
istream in(10,b) ;
```

is replaced by

```
char* buf[10] ;
istrstream in(b,10) ;
```

The old `istream()` constructor allowed an optional extra argument to specify skipping of whitespace. In the iostream library this is part of a greatly expanded collection of state variables and so an extra argument is not provided for the `istrstream()` constructor. However, the obsolete form of `istream()` constructor continues to accept these optional arguments.

Filebuf

Both libraries contain a `filebuf` class for using streams to do I/O. It is declared in `fstream.h` in the iostream library. The stream library had constructors that implied the use of `filebufs`. In the iostream library these constructors are replaced by constructors of certain derived classes. The old usage:

```
int fd ;
istream in(fd) ;   // file descriptor
ostream out(fd) ;  // file descriptor
```

is replaced by:

```
int fd ;
ifstream in(fd) ;  // file descriptor
ofstream out(fd) ; // file descriptor
```

The optional extra arguments of the stream constructors (for specifying whitespace skipping and "tying") are not supported. The equivalent functionality is supported by format state variables.

Interactions with stdio

The libraries differ significantly in the way they interact with stdio. The old stream header `stream.h` included `stdio.h` and some stream data structures could contain a pointer to a stdio `FILE`. In the iostream library specialized streams and streambufs (declared in `stdiostream.h`) are provided to make the connection.

The old usage:

```
FILE* stdiofile ;
filebuf fb(stdiofile) ;
istream in(stdiofile) ;
ostream out(stdiofile) ;
constructor, obsolete form
constructor, obsolete form
constructor, obsolete form
```

is replaced by:

```
FILE* stdiofile ;
stdiobuf fb(stdiofile) ;
stdiostream in(stdiofile) ;
stdiostream out(stdiofile) ;
```

In the old library the predefined streams `cin`, `cout`, and `cerr` were directly connected to the stdio `FILE`s `stdin`, `stdout`, and `stderr`. I/O was mixed character by character. Further, these streams were unbuffered in the sense that insertion and extraction was done by doing character by character puts and gets on the corresponding stdio `FILE`s. In the iostream library the predefined streams are attached directly to file descriptors rather than to the stdio streams. This means that for output the characters are mixed only as flushes are done and the input buffer of one is not visible to the other.

In practice the biggest problems seem to come from attempts to mix code that uses `stdout` with code that uses `cout`. The best solution is to cause flushes to be inserted whenever the program switches from one library to the other. An alternative is to use:

```
ios::sync_with_stdio() ;
```

This causes the predefined streams to be connected to the corresponding stdio files in an unbuffered mode. The major drawback of this solution is the large overheads associated with insertion of characters in this mode. Typically insertion into `cout` is slowed by a factor of 4 after a call of `sync_with_stdio()`.

The old stream library contained some "stringifying" functions that were called with various arguments and returned a string. These are declared in `stream.h` and available primarily for compatibility. The only such formatting function that seems to provide a significant functionality that is not easily available in the iostream library is `form()`, which allows `printf()` like formatting. In fact, `form()` is just a wrapper for calls to `sprintf()`. The programmer can easily write manipulators and inserters that do the same thing.

Assignment

In the old library it was possible to assign one stream to another. This is possible in the iostream library only if the left hand side is declared to be an assignable class. A general assignment cannot be allowed because of the interactions of derived classes. What, for example, should be the effect of assigning an `ifstream` to an `istrstream`? Most programs that use this feature can be converted by using a reference or pointer to a stream. The old usage:

```
ostream out ;
out = cout ;
out << x ;
```

can be replaced by:

```
ostream* out ;
out = cout ;
out << x ;
```

or:

```
ostream_with_assign out ;
out = &cout ;
*out << x ;
```

`char` Insertion Operator

The stream library did not contain an insertion operator for `char`. So inserting a `char` was taken as inserting an integer value, and it was converted to decimal. This omission was due to problems with overload resolution in earlier versions of the C++ Language System. Any old code such as:

```
char c ;
cout << c ;
```

may be replaced by:

```
char c ;
cout << (int)c ;
```

Index

```
class Y : public X {
        void mf();
};


Y::mf()
{
        priv = 1;               // error: priv is private
        prot = 2;               // OK: prot is protected and mf2() is a member of Y
        publ = 3;               // OK: publ is public
}


void f(Y* p)
{
        p->priv = 1;            // error: priv is private
        p->prot = 2;            // error: prot is protected and f() is not a friend
                                //        or a member of X or Y
        p->publ = 3;            // OK: publ is public
}
```

A more realistic example of the use of `protected` can be found in this chapter under "Multiple Inheritance."

A `friend` function has the same access to `protected` members as a member function.

A subtle point is that accessibility of protected members depends on the static type of the pointer used in the access. A member or a friend of a derived class has access only to protected members of objects that are known to be of its derived type. For example:

Manual Pages

To see an online manual page, type man name where name is a particular manual page. For example, to see the manual page for `ios`, type man ios.

The `complex` library manual pages are:

- *CPLX.INTRO(3C++)*
- *cartpol(3C++)*
- *cplxerr(3C++)*
- *cplxops(3C++)*
- *cplxexp(3C++)*
- *cplxtrig(3C++)*

The `task` library manual pages are:

- *TASK.INTRO(3C++)*
- *task(3C++)*
- *queue(3C++)*
- *interrupt(3C++)*
- *tasksim(3C++)*

The `iostream` library manual pages are:

- *IOS.INTRO(3C++)*
- *ios(3C++)*
- *sbuf.pub(3C++)*
- *sbuf.prot(3C++)*
- *filebuf(3C++)*
- *stdiobuf(3C++)*
- *ssbuf(3C++)*
- *istream(3C++)*
- *ostream(3C++)*
- *fstream(3C++)*
- *strstream(3C++)*
- *manip(3C++)*

NAME

complex – introduction to C++ complex mathematics library

SYNOPSIS

```
#include <complex.h>
class complex;
```

DESCRIPTION

This section describes functions and operators found in the C++ Complex Mathematics Library, `libcomplex.a`. These functions are not automatically loaded by the C++ compiler, `CC`(1); however, the link editor searches this library under the `-lcomplex` option. Declarations for these functions may be found in the `#include` file `<complex.h>`. When compiling programs using the complex library, users must provide the `-lm` options on the `CC` command line to link the math library.

The Complex Mathematics library implements the data type of complex numbers as a class, `complex`. It overloads the standard input, output, arithmetic, assignment, and comparison operators, discussed in the manual pages for `cplxops`(3C++). It also overloads the standard exponential, logarithm, power, and square root functions, discussed in `cplxexp`(3C++), and the trigonometric functions of sine, cosine, hyperbolic sine, and hyperbolic cosine, discussed in `cplxtrig`(3C++), for the class `complex`. Routines for converting between Cartesian and polar coordinate systems are discussed in `cartpol`(3C++). Error handling is described in `cplxerr`(3C++).

FILES

```
INCDIR/complex.h
LIBDIR/libcomplex.a
```

SEE ALSO

`cartpol`(3C++), `cplxerr`(3C++), `cplxops`(3C++), `cplxexp`(3C++), and `cplxtrig`(3C++).
Stroustrup, B., "Complex Arithmetic in C++," Chapter 1 of the *C++ Language System Release 2.1 Library Manual.*

DIAGNOSTICS

Functions in the Complex Mathematics Library (3C++) may return the conventional values `(0, 0)`, `(0, ±HUGE)`, `(±HUGE, 0)`, or `(±HUGE, ±HUGE)`, when the function is undefined for the given arguments or when the value is not representable. (`HUGE` is the largest-magnitude single-precision floating-point number and is defined in the file `<math.h>`. The header file `<math.h>` is included in the file `<complex.h>`.) In these cases, the external variable `errno` [see `intro`(2)] is set to the value `EDOM` or `ERANGE`.

NAME

task – coroutines, multiple threads of control, C++ task library

SYNOPSIS

```
#include <task.h>

class object;
class sched : public object;
class timer : public sched;
class task  : public sched;

class qhead : public object;
class qtail : public object;

class Interrupt_handler : public object;

class histogram;
class randint;
class urand : public randint;
class erand : public randint;
```

DESCRIPTION

The C++ task library provides facilities for writing programs with multiple threads of control within one UNIX system process. Each thread of control is a `task` or coroutine. Each `task` is an instance of a user-defined class derived from class `task`, and the main program of the `task` is the constructor of its class. A `task` can be suspended and resumed without interfering with its internal state. Each `task` runs until it explicitly gives up the processor; there is no pre-emption.

Most classes in the task system are derived from the base class `object`. The base class `sched` is responsible for scheduling and for the functionality that is common to `task`s and `timer`s. Class `sched` is meant to be used strictly as a base class, that is, it is illegal to create objects of class `sched`. Class `task` must also be used only as a base class. The programmer must derive a class from class `task`, and provide a constructor to serve as the `task`'s main program. The task system can be used for writing event-driven simulations. `task`s execute in a simulated time frame. Objects of class `timer` provide a facility for implementing time-outs and other time-dependent phenomena. Classes `task`, `timer`, `sched`, and `object` and their public member functions are described on the `task`(3C++) manual page.

Classes `qhead` and `qtail` enable a wide range of message-passing and data-buffering schemes to be implemented simply. These classes are described on the `queue`(3C++) manual page.

Class `Interrupt_handler` provides an interface for writing classes that can wait for external events using UNIX system signals. These classes are described on the `interrupt`(3C++) manual page.

Class `histogram` aids data gathering. Classes `randint`, `urand`, and `erand` provide random number generation. These four classes are described on the `tasksim`(3C++) manual page.

SEE ALSO

`task`(3C++), `queue`(3C++), `interrupt`(3C++), `tasksim`(3C++)
Stroustrup, B. and Shopiro, J. E., "A Set of C++ Classes for Co-routine Style Programming," in Chapter 2 of the *AT&T C++ Language System Release 2.1 Library Manual.*
Shopiro, J. E., "Extending the C++ Task System for Real-Time Control," in Chapter 2 of the *AT&T C++ Language System Release 2.1 Library Manual.*

NAME

iostream – buffering, formatting and input/output

SYNOPSIS

```
#include <iostream.h>
class streambuf ;
class ios ;
class istream : virtual public ios ;
class ostream : virtual public ios ;
class iostream : public istream, public ostream ;
class istream_withassign : public istream ;
class ostream_withassign : public ostream ;
class iostream_withassign : public iostream ;

class Iostream_init ;

extern istream_withassign cin ;
extern ostream_withassign cout ;
extern ostream_withassign cerr ;
extern ostream_withassign clog ;

#include <fstream.h>
class filebuf : public streambuf ;
class fstream : public iostream ;
class ifstream : public istream ;
class ofstream : public ostream ;

#include <strstream.h>
class strstreambuf : public streambuf ;
class istrstream : public istream ;
class ostrstream : public ostream ;

#include <stdiostream.h>
class stdiobuf : public streambuf ;
class stdiostream : public ios ;
```

DESCRIPTION

The C++ iostream package declared in `iostream.h` and other header files consists primarily of a collection of classes. Although originally intended only to support input/output, the package now supports related activities such as incore formatting. This package is a mostly source-compatible extension of the earlier stream I/O package, described in *The C++ Programming Language* by Bjarne Stroustrup.

In the iostream man pages, *character* refers to a value that can be held in either a `char` or `unsigned char`. When functions that return an `int` are said to return a character, they return a positive value. Usually such functions can also return `EOF` (−1) as an error indication. The piece of memory that can hold a character is referred to as a *byte*. Thus, either a `char*` or an `unsigned char*` can point to an array of bytes.

The iostream package consists of several core classes, which provide the basic functionality for I/O conversion and buffering, and several specialized classes derived from the core classes. Both groups of classes are listed below.

Core Classes

The core of the iostream package comprises the following classes:

`streambuf`

This is the base class for buffers. It supports insertion (also known as `storing` or `putting`) and extraction (also known as `fetching` or `getting`) of characters. Most members are inlined for efficiency. The public interface of class `streambuf` is described in `sbuf.pub`(3C++) and the protected interface (for derived classes) is described in `sbuf.prot`(3C++).

ios
This class contains state variables that are common to the various stream classes, for example, error states and formatting states. See ios(3C++).

istream
This class supports formatted and unformatted conversion from sequences of characters fetched from streambufs. See istream(3C++).

ostream
This class supports formatted and unformated conversion to sequences of characters stored into streambufs. See ostream(3C++).

iostream
This class combines istream and ostream. It is intended for situations in which bidirectional operations (inserting into and extracting from a single sequence of characters) are desired. See ios(3C++).

istream_withassign
ostream_withassign
iostream_withassign
These classes add assignment operators and a constructor with no operands to the corresponding class *without assignment*. The predefined streams (see below) cin, cout, cerr, and clog, are objects of these classes. See istream(3C++), ostream(3C++), and ios(3C++).

Iostream_init
This class is present for technical reasons relating to initialization. It has no public members. The Iostream_init constructor initializes the predefined streams (listed below). Because an object of this class is declared in the iostream.h header file, the constructor is called once each time the header is included (although the real initialization is only done once), and therefore the predefined streams will be initialized before they are used. In some cases, global constructors may need to call the Iostream_init constructor explicitly to ensure the standard streams are initialized before they are used.

Predefined streams

The following streams are predefined:

cin	The standard input (file descriptor 0).
cout	The standard output (file descriptor 1).
cerr	Standard error (file descriptor 2). Output through this stream is unit-buffered, which means that characters are flushed after each inserter operation. (See ostream::osfx() in ostream(3C++) and ios::unitbuf in ios(3C++).)
clog	This stream is also directed to file descriptor 2, but unlike cerr its output is buffered.

cin, cerr, and clog are tied to cout so that any use of these will cause cout to be flushed.

In addition to the core classes enumerated above, the iostream package contains additional classes derived from them and declared in other headers. Programmers may use these, or may choose to define their own classes derived from the core iostream classes.

Classes derived from streambuf

Classes derived from streambuf define the details of how characters are produced or consumed. Derivation of a class from streambuf (the protected interface) is discussed in sbuf.prot(3C++). The available buffer classes are:

filebuf
This buffer class supports I/O through file descriptors. Members support opening, closing, and seeking. Common uses do not require the program to manipulate file descriptors. See filebuf(3C++).

stdiobuf
This buffer class supports I/O through stdio FILE structs. It is intended for use when mixing C and C++ code. New code should prefer to use filebufs. See stdiobuf(3C++).

`strstreambuf`
: This buffer class stores and fetches characters from arrays of bytes in memory (i.e., strings). See `ssbuf`(3C++).

Classes derived from `istream`, `ostream`, and `iostream`

Classes derived from `istream`, `ostream`, and `iostream` specialize the core classes for use with particular kinds of `streambufs`. These classes are:

`ifstream`
`ofstream`
`fstream`
: These classes support formatted I/O to and from files. They use a `filebuf` to do the I/O. Common operations (such as opening and closing) can be done directly on streams without explicit mention of `filebufs`. See `fstream`(3C++).

`istrstream`
`ostrstream`
: These classes support "in core" formatting. They use a `strstreambuf`. See `strstream`(3C++).

`stdiostream`
: This class specializes `iostream` for stdio `FILE`s. See `stdiostream.h`.

CAVEATS

Parts of the `streambuf` class of the old stream package that should have been private were public. Most normal usage will compile properly, but any code that depends on details, including classes that were derived from `streambufs`, will have to be rewritten.

Performance of programs that copy from `cin` to `cout` may sometimes be improved by breaking the tie between `cin` and `cout` and doing explicit flushes of `cout`.

The header file `stream.h` exists for compatibility with the earlier stream package. It includes `iostream.h`, `stdio.h`, and some other headers, and it declares some obsolete functions, enumerations, and variables. Some members of `streambuf` and `ios` (not discussed in these man pages) are present only for backward compatibility with the stream package.

SEE ALSO

`ios`(3C++), `sbuf.pub`(3C++), `sbuf.prot`(3C++), `filebuf`(3C++), `stdiobuf`(3C++), `ssbuf`(3C++), `istream`(3C++), `ostream`(3C++), `fstream`(3C++), `strstream`(3C++), and `manip`(3C++)

C++ Language System Release 3.0.1

Selected Readings

Contents

Figures and Tables

Preface

The *AT&T C++ Language System Selected Readings* contains papers about the C++ programming language. The manual is part of a set of four documents that are supplied with your C++ Language System. The other documents are:

- the *Release Notes*, which describe the contents of this release, how to install it, and changes to the language
- the *Product Reference Manual*, which provides a complete definition of the C++ language supported by the Release 3.0 C++ Language System
- the *Library Manual*, which describes the three C++ class libraries and tells you how to use them

The twelve chapters in this manual are based on technical memoranda by authors working with various aspects of the C++ language. These chapters cover features of the language provided by Release 3.0 of the compiler. Chapters 7 and 8, which describe the template feature, have been updated to reflect changes in this feature in Release 3.0.1. These are the only chapters which have been changed since Release 3.0.

- Chapter 1 lists the new features of C++ and describes each one briefly
- Chapter 2 is a tutorial showing you how to use the special features that C++ provides
- Chapter 3 is an overview of the language provided with Release 3.0
- Chapter 4 describes support for object-oriented programming in C++
- Chapter 5 explains the multiple inheritance feature and describes its use
- Chapter 6 discusses parameterized types in C++
- Chapter 7 gives an overview of the implmentation of template instantiation in C++ Release 3.0
- Chapter 8 provides a user's guide to template instantiation
- Chapter 9 explains the type-safe linkage capabilities
- Chapter 10 explains levels of protection in C++ class definitions
- Chapter 11 explains inline functions in C++
- Chapter 12 discusses C++ and ANSI C

To make the best use of the *Selected Readings,* you should be familiar with the C programming language and the C programming environment under the UNIX operating system.

Acknowledgements

- Chapter 1 is based on the paper, "The Evolution of C++; 1985 to 1989," by Bjarne Stroustrup. That paper acknowledges the following contributions:

  Most of the credit for these extensions goes to the literally hundreds of C++ users who provided me with bugs, mistakes, suggestions, and most importantly with sample problems.

  Phil Brown, Tom Cargill, Jim Coplien, Steve Dewhurst, Keith Gorlen, Laura Eaves, Bob Kelley, Brian Kernighan, Andy Koenig, Archie Lachner, Stan Lippman, Larry Mayka, Doug McIlroy, Pat Philip, Dave Prosser, Peggy Quinn, Roger Scott, Jerry Schwarz, Jonathan Shopiro, and Kathy Stark supplied many valuable suggestions and questions.

  The C++ multiple inheritance mechanism was partially inspired by the work of Stein Krogdahl from the University of Oslo.

- Chapter 2 is based on the paper, "An Introduction to C++," by Keith Gorlen.

- Chapter 3 is based on the paper, "An Overview of C++," by Bjarne Stroustrup, published in *ACM Sigplan Notices*, October 1986, pp. 7-18. That paper acknowledges the following contributions:

  C++ could never have matured without the constant help and constructive criticism of my colleagues and users; notably Tom Cargill, Jim Coplein, Stu Feldman, Sandy Fraser, Steve Johnson, Brian Kernighan, Bart Locanthi, Doug McIlroy, Dennis Ritche, Ravi Sethi, and Jon Shopiro. Brian Kernighan and Andy Koenig made many helpful comments on drafts of this paper.

- Chapter 4 is based on a paper first presented at the Association of Simula Users' meeting in Stockholm, August 1986. Later, a version was presented as an invited talk at the first European Conference on Object-Oriented Programming in Paris and published by Springer Verlag. It also appeared in the May 1988 issue of IEEE Software Magazine. This version has been revised to reflect the latest version of as described in *The Annotated Reference Manual* by M.A. Ellis and B. Stroustrup (Addison-Wesley, 1990) approved by the ANSI C++ committee (X3J16) as the basis of formal standardization. The paper acknowledges the following contributions:

  An earlier version of this paper was presented to the Association of Simula Users meeting in Stockholm. The discussions there caused many improvements both in style and content. Brian Kernighan and Ravi Sethi made many constructive comments. Also thanks to all who helped shape C++.

- Chapter 5 is based on the paper, "Multiple Inheritance for C++," by Bjarne Stroustrup, published in the proceedings of the EUUG Spring Conference, May 1987 (revised for this manual). That paper acknowledges the following contributions:

  In 1984 I had a long discussion with Stein Krogdahl from the University of Oslo, Norway. He had devised a scheme for implementing multiple inheritance in Simula using pointer manipulation based on addition and subtraction of constants. His paper, "An Efficient Implementation of Simula Classes with Multiple Prefixing" (Research Report No. 83, June 1984, University of Oslo, Institute of Informatics) describes this work. Tom Cargill, Jim Coplien, Brian Kernighan, Andy Koenig, Larry Mayka, Doug McIlroy, and Jonathan Shopiro sopplied many valuable suggestions and questions.

- Chapter 6 is based on the paper "Parameterized Types for C++, " by Bjarne Stroustrup. The paper acknowledges the following contributions:

  Andy Koenig, Jon Shopiro, and Alex Stepanov wrote many template-style macros to help determine what language features was needed to support this style of programming. Jim Coplien, Margaret Ellis, Brian Kernighan, and Doug McIlroy supplied many valuable suggestions and questions.

- Chapter 7 is based on the paper "Template Instantiation in C++ Release 3.0" by Glen McCluskey and Robert B. Murray. The paper acknowledges the following contributions:

  Thanks to Steve Buroff, Martin Carroll, Tony Hansen, Andrew Koenig, Michey Mehta, Barbara Moo, Bjarne Stroustrup, Judy Ward, and Clay Wilson for helpful comments and criticisms.

- Chapter 8 is based on the paper "Template Instantiation in C++ Release 3.0 – User Guide" by Glen McCluskey.

- Chapter 9 is based on the paper, "Type-Safe Linkage for C++," by Bjarne Stroustrup, published in *Computing Systems*, Volume VI, no. 4, Fall 1988, pp. 371-404. That paper acknowledges the following contributions:

  The new linkage and overloading scheme was essentially a joint effort of Andrew Koenig, Doug McIlroy, Jerry Schwarz, Jonathan Shopiro, and me. Brian Kernighan made many useful comments. The name encoding scheme is based on a proposal by Stan Lippman and Steve Dewhurst with input from Andrew Koenig and me. Steve Dewhurst, Bill Hopkins, Jim Howard, Mike Mowbray, Tim O'Konski, and Roger Scott also made valuable comments on earlier versions on this paper.

- Chapter 10 is based on the paper, "Access Rules for C++," by Phil Brown.

- Chapter 11 is based on the paper, "Inline Functions in C++," by Dennis Mancl.

- Chapter 12 is based on the paper, "As Close as Possible to C — But No Closer," by Andrew Koenig and Bjarne Stroustrup, published in the C++ *Report*, Volume I, no. 7, July–August 1989. That paper acknowledges the following contributions:

  We would like to thank the many C and C++ users who have commented on the relationship between C and C++ and made suggestions about both the ideals and the thorny details of this sensitive topic. In particular we would like to thank Doug McIlroy, David Prosser, and Margaret Quinn.

1 Evolution of C++

The Evolution of C++: 1985 to 1989

NOTE This chapter is taken directly from a paper by Bjarne Stroustrup.

Abstract

The C++ Programming Language describes C++ as defined and implemented in August 1985. This paper describes the growth of the language since then and clarifies a few points in the definition. It is emphasized that these language modifications are extensions; C++ has been and will remain a stable language suitable for long term software development. The main new features of C++ are: multiple inheritance, type-safe linkage, better resolution of overloaded functions, recursive definition of assignment and initialization, better facilities for user-defined memory management, abstract classes, `static` member functions, `const` member functions, `protected` members, overloading of operator ->, and pointers to members. These features are provided in the 2.1 release of C++.

Introduction

As promised in *The C++ Programming Language*, C++ has been evolving to meet the needs of its users. This evolution has been guided by the experience of users of widely varying backgrounds working in a great range of application areas. The primary aim of the extensions has been to enhance C++ as a language for data abstraction and object-oriented programming in general and to enhance it as a tool for writing high-quality libraries of user-defined types in particular. By a high-quality library I mean a library that provides a concept to a user in the form of one or more classes that are convenient, safe, and efficient to use. In this context, *safe* means that a class provides a specific type-secure interface between the users of the library and its providers; *efficient* means that use of the class does not impose large overhead in run-time or space on the user compared with hand written C code.

Portability of at least some C++ implementations is a key design goal. Consequently, extensions that would add significantly to the porting time or to the demands on resources for a C++ compiler have been avoided. This ideal of language evolution can be contrasted with plausible alternative directions such as making programming convenient

- at the expense of efficiency or structure;
- for novices at the expense of generality;
- in a specific application area by adding special purpose features to the language;
- by adding language features to increase integration into a specific C++ environment

For some ideas of where these ideas of language evolution might lead C++ see Chapter 4.

A programming language is only one part of a programmer's world. Naturally, work is being done in many other fields (such as tools, environments, libraries, education and design methods) to make C++ programming more pleasant and effective. This paper, however, deals strictly with language and language implementation issues.

Overview

This paper is a brief overview of new language features; it is not a manual or a tutorial. The reader is assumed to be familiar with the language as described in *The C++ Programming Language* and to have sufficient experience with C++ to recognize many of the problems that the features described here are designed to solve or alleviate. Most of the extensions take the form of removing restrictions on what can be expressed in C++.

- Access Control

  First some extensions to C++'s mechanisms for controlling access to class members are presented. Like all extensions described here, they reflect experience with the mechanisms they extend and the increased demands posed by the use of C++ in relatively large and complicated projects.

- Overloading Resolution
- Type-Safe Linkage

  C++ software is increasingly constructed by combining semi-independent components (modules, classes, libraries, etc.) and much of the effort involved in writing C++ goes into the design and implementation of such components. To help these activities, the rules for overloading function names and the rules for linking separately compiled code have been refined.

- Multiple Inheritance
- Base and Member Initialization
- Abstract Classes

  Classes are designed to represent general or application specific concepts. Originally, C++ provided only single inheritance, that is, a class could have at most one direct base class, so that the directly representable relations between classes had to be a tree structure. This is sufficient in a large majority of cases. However, there are important concepts for which relations cannot be naturally expressed as a tree, but where a directed acyclic graph is suitable. As a consequence, C++ has been extended to support multiple inheritance, that is, a class can have several immediate base classes, directly. The rules for ambiguity resolution and for initialization of base classes and members have been refined to cope with this extension.

- `static` Member Functions
- `const` Member Functions

- Initialization of `static` Members
- Pointers to Members

  The concept of a class member has been generalized. Most important, the introduction of `const` member functions allows the rules for `const` class objects to be enforced.
- User-Defined Free Store Management

  The mechanisms for user-defined memory management have been refined and extended to the point where the old and inelegant "assignment to `this`" mechanism has become redundant.
- Assignment and Initialization

  The rules for assignment and initialization of class objects have been made more general and uniform to require less work from the programmer.
- Operator ->
- Operator ,
- Initialization of `static` objects
- Some minor extensions are presented.
- Resolutions

  The last section does not describe language extensions but presents the resolution of some details of the C++ language definition.
- In addition to the extensions mentioned here, many details of the definition of C++ have been modified for greater compatibility with the proposed ANSI C standard.

Access Control

The rules and syntax for controlling access to class members have been made more flexible.

`protected` Members

The simple private/public model of data hiding served C++ well where C++ was used essentially as a data abstraction language and for a large class of problems where inheritance was used for object-oriented programming. However, when derived classes are used there are two kinds of users of a class: derived classes and "the general public." The members and friends that implement the operations on the class operate on the class objects on behalf of these users. The private/public mechanism allows the programmer to distinguish clearly between the implementors and the general public, but does not provide a way of catering specifically to derived classes. This often caused the data hiding mechanisms to be ignored:

```
class Y : public X {
        void mf();
};

Y::mf()
{
        priv = 1;               // error: priv is private
        prot = 2;               // OK: prot is protected and mf2() is a member of Y
        publ = 3;               // OK: publ is public
}

void f(Y* p)
{
        p->priv = 1;            // error: priv is private
        p->prot = 2;            // error: prot is protected and f() is not a friend
                                //        or a member of X or Y
        p->publ = 3;            // OK: publ is public
}
```

A more realistic example of the use of `protected` can be found in this chapter under "Multiple Inheritance."

A `friend` function has the same access to `protected` members as a member function.

A subtle point is that accessibility of protected members depends on the static type of the pointer used in the access. A member or a friend of a derived class has access only to protected members of objects that are known to be of its derived type. For example:

```
class Z : public Y {
        // ...
};


void Y::mf()
{
        prot = 2;       // OK: prot is protected and mf() is a member function

        X a;
        a.prot = 3;     // error: prot is protected and a is not a Y

        X* p = this;
        p->prot = 3;    // error: prot is protected
                        //        and p is not a pointer to Y

        Z b;
        b.prot = 4;     // OK: prot is protected
                        //     and mf() is a member and a Z is a Y
}
```

A protected member of a class base is a protected member of a class derived from base if the derivation is public and private otherwise.

Access Control Syntax

The following example confuses most beginners and even experts get bitten sometimes:

```
class X {
        // ...
public:
        int f();
};

class Y : X { /* ... */ };


int g(Y* p)
{
        // ...
        return p->f();          // error!
};
```

Here X is by default declared to be a private base class of Y. This means that X is not a subtype of Y so the call p->f() is illegal because Y does not have a public function f(). Private base classes are quite an important concept, but to avoid confusion it is recommended that they be declared private explicitly:

```
class Y : private X { /* ... */ };
```

Several public, private, and protected sections are allowed in a class declaration:

```
class X {
public:
        int i1;
private:
        int i2;
public:
        int i3;
};
```

These sections can appear in any order. This implies that the public interface of a class may appear textually before the private "implementation details":

```
class S {
public:
        f();
        int i1;
        // ...
private:
        g();
        int i2;
        // ...
};
```

Adjusting Access

When a class base is used as a private base class all of its members are considered private members of the derived class. The syntax *base-class-name* :: *member-name* can be used to restore access of a member to what it was in the base:

```
class base {
public:
        int publ;
protected:
        int prot;
private:
        int priv;
};
```

```
class derived : private base {
protected:
        base::prot;             // protected in derived
public:
        base::publ;             // public in derived
};
```

This mechanism cannot be used to grant access that was not already granted by the base class:

```
class derived2 : public base {
public:
        base::priv;             // error: base::priv is private
};
```

This mechanism can be used only to restore access to what it was in the base class:

```
class derived3: private base {
protected:
        base::publ;             // error: base::publ was public
};
```

This mechanism cannot be used to remove access already granted:

```
class derived4: public base {
private:
        base::publ;             // error: base::publ is public
};
```

We considered allowing the last two forms and experimented with them, but found that they caused total confusion among users about the access control rules and the rules for private and public derivation. Similar considerations led to the decision not to introduce the (otherwise perfectly reasonable) concept of protected base classes.

Details

A friend function has the same access to base class members as a member function. For example:

```
class base {
protected:
        int prot;
public:
        int pub;
};


class derived : private base {
public:
        friend int fr(derived *p) { return p->prot; }
        int mem() { return prot; }
};
```

In particular, a friend function can perform the conversion of a pointer to a derived class to its private base class:

```
class derived2 : private base {
public:
        friend base* fr(derived *p) { return p; }
        base* mem() { return this; }
};


base* f(derived* p)
{
        return p;               // error: cannot convert;
                                // base is a private base class of derived
}
```

However, friendship is *not* transitive. For example:

```
class X {
friend class Y;
private:
        int a;
};


class Y {
        friend int fr(Y *p)
                { return p->a; }  // error: fr() is not a friend of X
        int mem(Y* p)
                { return p->a; }  // OK: mem() is a friend of X
};
```

Overloading Resolution

The C++ overloading mechanism was revised to allow resolution of types that used to be "too similar" and to gain independence of declaration order. The resulting scheme is more expressive and catches more ambiguity errors. Consider:

```
double abs(double);
float abs(float);
```

To cope with single precision floating point arithmetic it must be possible to declare both of these functions; now it is. The effect of any call of `abs()` given the declarations above is the same if the order of declarations was reversed:

```
float abs(float);
double abs(double);
```

Here is a slightly simplified explanation of the new rules. Note that with the exception of a few cases where the the older rules allowed order dependence the new rules are compatible and old programs produce identical results under the new rules. For the last two years or so C++ implementations have issued warnings for the now "outlawed" order dependent resolutions.

C++ distinguishes five kinds of "matches":

- Match using no or only unavoidable conversions (for example, array name to pointer, function name to pointer to function, and `T` to `const T`).
- Match using integral promotions (as defined in the proposed ANSI C standard; that is, `char` to `int`, `short` to `int` and their `unsigned` counterparts) and `float` to `double`.
- Match using standard conversions (for example, `int` to `double`, `derived*` to `base*`, `unsigned int` to `int`).
- Match using user defined conversions (both constructors and conversion operators).
- Match using the ellipsis `...` in a function declaration.

Consider first functions of a single argument. The idea is always to choose the "best" match, that is the one highest on the list above. If there are two best matches the call is ambiguous and thus a compile time error. For example,

```
float abs(float);
double abs(double);
int abs(int);
unsigned abs(unsigned);
char abs(char);


abs(1);                         // abs(int);
abs(1U);                        // abs(unsigned);
abs(1.0);                       // abs(double);
abs(1.0F);                      // abs(float);
abs('a');                       // abs(char);
abs(1L);                        // error: ambiguous, abs(int) or abs(double)
```

Here, the calls take advantage of the ANSI C notation for `unsigned` and `float` literals and of the C++ rule that a character constant is of type `char` [1]. The call with the `long` argument `1L` is ambiguous since `abs(int)` and `abs(double)` would be equally good matches (match with standard conversion).

Hierarchies established by public class derivations are taken into account in function matching and where a standard conversion is needed the conversion to the "most derived" class is chosen. A `void*` argument is chosen only if no other pointer argument matches. For example:

```
class B { /* ... */ };
class BB : public B { /* ... */ };
class BBB : public BB { /* ... */ };


f(B*);
f(BB*);
f(void*);


void g(BBB* pbbb, int* pi)
{
        f(pbbb);                // f(BB*);
        f(pi);                  // f(void*);
}
```

This ambiguity resolution rule matches the rule for virtual function calls where the member from the most derived class is chosen.

If two otherwise equally good matches differ in terms of `const`, the `const` specifier is taken into account in function matching for pointer and reference arguments. For example:

```
char* strtok(char*, const char*);
const char* strtok(const char*, const char*);

void g(char* vc, const char* vcc)
{
        char* p1 = strtok(vc,"a");// strtok(char*, char*);
        const char* p2 = strtok(vcc,"a");// strtok(const char*, char*);
        char* p3 = strtok(vcc,"a");// error
}
```

In the third case, `strtok(const char*, const char*)` is chosen because `vcc` is a `const char*`. This leads to an attempt to initialize the `char* p3` with the `const char*` result.

For calls involving more than one argument a function is chosen provided it has a better match than every other function for at least one argument and at least as good a match as every other function for every argument. For example:

```
class complex { ... complex(double); };

f(int,double);
f(double,int);
f(complex,int);
f(int ...);
f(complex ...);


complex z = 1;

f(1, 2.0);          // f(int,double);
f(1.0, 2);          // f(double,int);
f(z, 1.2);          // f(complex,int);
f(z, 1, 3);         // f(complex ...);
f(2.0, z);          // f(int ...);
f(1, 1);            // error: ambiguous, f(int,double) and f(double,int)
```

The unfortunate narrowing from `double` to `int` in the third and the second to last cases causes warnings. Such narrowings are allowed to preserve compatibility with C. In this particular case the narrowing is harmless, but in many cases `double` to `int` conversions are value destroying and they should never be used thoughtlessly.

As ever, at most one user-defined and one built-in conversion may be applied to a single argument.

Type-Safe Linkage

Originally, C++ allowed a name to be used for more than one name ("to be overloaded") only after an explicit `overload` declaration. For example:

```
overload max;                   // 'overload' now obsolete
int max(int,int);
double max(double,double);
```

It used to be considered too dangerous simply to use a name for two functions without previous declaration of intent. For example:

```
int abs(int);
double abs(double);             // used to be an error
```

This fear of overloading had two sources:

- concern that undetected ambiguities could occur
- concern that a program could not be properly linked unless the programmer explicitly declared where overloading was to take place.

The former fear proved largely groundless and the few problems found in actual use have been taken care of by the new order-independent overloading resolution rules. The latter fear proved to have a basis in a general problem with C separate compilation rules that had nothing to do with overloading.

On the other hand, the redundant `overload` declarations themselves became an increasingly serious problem. Since they had to precede (or be part of) the declarations they were to enable, it was not possible to merge pieces of software using the same function name for different functions unless both pieces had declared the function overloaded. This is not usually the case. In particular, the name one wants to overload is often the name of a C standard library function declared in a C header. For example, one might have standard headers like this:

```
/* Header for C standard math library, math.h: */
        double sqrt(double);
        /* ... */


// header for C++ standard complex arithmetic library, complex.h:
        overload sqrt;
        complex sqrt(complex);
        // ...
```

and try to use them like this:

```
#include <math.h>
#include <complex.h>
```

This causes a compile time error when the `overload` for `sqrt()` is seen after the first declaration of `sqrt()`. Rearranging declarations, putting constraints on the use of header files, and sprinkling `overload` declarations everywhere "just in case" can alleviate this kind of problem, but we found the use of such tricks unmanageable in all but the simplest cases. Abolishing `overload` declarations (and getting rid of the `overload` keyword in the process) is a much better idea.

Doing things this way does pose an implementation problem, though. When a single name is used for several functions, one must be able to tell the linker which calls are to be linked to which function definitions. Ordinary linkers are not equipped to handle several functions with the same name. However, they can be tricked into handling overloaded names by encoding type information into the names seen by the linker. For example, the names for these two functions:

```
double sqrt(double);
complex sqrt(complex);
```

become:

```
sqrt__Fd
sqrt__F7complex
```

in the compiler output to the linker. The user and the compiler see the C++ source text where the type information serves to disambiguate and the linker sees the names that have been disambiguated by adding a textual representation of the type information. Naturally, one might have a linker that understood about type information, but it is not necessary and such linkers are certainly not common.

Using this encoding or any equivalent scheme solves a long standing problem with C linkage. Inconsistent function declarations in separately compiled code fragments are now caught. For example:

```
// file1.c:

extern name* lookup(table* tbl, const char* name);

// ...

void some_fct(char* s)
{
      name* n = lookup(gtbl,s);
}
```

looks plausible and the compiler can find no fault with it. However, if the definition of `lookup()` turns out to be:

```
// file2.c:

int lookup(table* tbl, const char* name, int index)
{
        // ...
}
```

the linker now has enough information to catch the error.

Finally, we have to face the problem of linking to code fragments written in other languages that do not know the C++ type system or use the C++ type encoding scheme. One could imagine all compilers for all languages on a system agreeing on a type system and a linkage scheme such that linkage of code fragments written in different languages would be safe. However, since this will not typically be the case we need a way of calling functions written in a language that does not use a type-safe linkage scheme and a way to write C++ functions that obey the different (and typically unsafe) linkage rules for other languages. This is done by explicitly specifying the name of the desired linkage convention in a declaration:

```
extern "C" double sqrt(double);
```

or by enclosing whole groups of declarations in a linkage directive:

```
extern "C" {
#include <math.h>
}
```

By applying the second form of linkage directive to standard header files one can avoid littering the user code with linkage directives. This type-safe linkage mechanism is discussed in detail in Chapter 6.

Multiple Inheritance

Consider writing a simulation of a network of computers. Each node in the network is represented by an object of class `Switch`, each user or computer by an object of class `Terminal`, and each communication line by an object of class `Line`. One way to monitor the simulation (or a real network of the same structure) would be to display the state of objects of various classes on a screen. Each object to be displayed is represented as an object of class `Displayed`. Objects of class `Displayed` are under control of a display manager that ensures regular update of a screen and/or data base. The classes `Terminal` and `Switch` are derived from a class `Task` that provides the basic facilities for co-routine style behavior. Objects of class `Task` are under control of a task manager (scheduler) that manages the real processor(s).

Ideally `Task` and `Displayed` are classes from a standard library. If you want to display a terminal, class `Terminal` must be derived from class `Displayed`. Class `Terminal`, however, is already derived from class `Task`. In a single inheritance language, such as Simula67, we have only two ways of solving this problem: deriving `Task` from `Displayed` or deriving `Displayed` from `Task`. Neither is ideal since they both create a dependency between the library versions of two fundamental and independent concepts. Ideally, one would want to be able to say that a `Terminal` is a `Task` *and* a `Displayed`; that a `Line` is a `Displayed` *but not* a `Task`; and that a `Switch` is a `Task` *but not* a `Displayed`.

The ability to express this class hierarchy, that is, to derive a class from more than one base class, is usually referred to as *multiple inheritance*. Other examples involve the representation of various kinds of windows in a window system and the representation of various kinds of processors and compilers for a multi-machine, multi-environment debugger.

In general, multiple inheritance allows a user to combine concepts represented as classes into a composite concept represented as a derived class. C++ allows this to be done in a general, type-safe, compact, and efficient manner. The basic scheme allows independent concepts to be combined and ambiguities to be detected at compile time. An extension of the base class concept, called *virtual base classes*, allows dependencies between classes in an inheritance DAG (Directed Acyclic Graph) to be expressed.

Ambiguous uses are detected at compile time:

```
class A { f(); /* ... */ };
class B { f(); /* ... */ };
class C : public A, public B { };


void g() {
        C* p;
        p->f();            // error: ambiguous
}
```

Note that it is not an error to combine classes containing the same member names in an inheritance DAG. The error occurs only when a name is used in an ambiguous way — and only then does the compiler have to reject the program. This is important since most potential ambiguities in a program never appear as actual ambiguities. Considering a potential ambiguity an error would be far too restrictive[2].

Typically one would resolve the ambiguity by adding a function:

```
class C : public A, public B {
public:
        f()
        {
                // C's own stuff
                A::f();
                B::f();
        }
        // ...
};
```

This example shows the usefulness of naming members of a base class explicitly with the name of the base class. In the restricted case of single inheritance, this way is marginally less elegant than the approach taken by Smalltalk and other languages (simply referring to "my super class" instead of using an explicit name). However, the C++ approach extends cleanly to multiple inheritance.

A class can appear more than once in an inheritance DAG:

```
class A : public L { /* ... */ };
class B : public L { /* ... */ };
class C : public A, public B { /* ... */ };
```

In this case, an object of class `C` has two sub-objects of class `L`, namely `A::L` and `B::L`. This is often useful, as in the case of an implementation of lists requiring each element on a list to contain a link element. If in the example above `L` is a link class then a `C` can be on both the list of `A`s and the list of `B`s at the same time.

Virtual functions work as expected; that is the version from the most derived class is used:

```
class A { public: virtual f(); /* ... */ };
class B { public: virtual g(); /* ... */ };
class C : public A, public B { public: f(); g(); /* ... */ };


void ff()
{
        C obj;
        A* pa = &obj;
        B* pb = &obj;

        pa->f();                // calls C::f
        pb->g();                // calls C::g
}
```

This way of combining classes is ideal for representing the union of independent or nearly independent concepts. However, in some interesting cases, such as the window example, a more explicit way of expressing sharing and dependency is needed.

Virtual base classes provide a mechanism for sharing between sub-objects in an inheritance DAG and for expressing dependencies among such sub-objects:

```
class A : public virtual W { /* ... */ };
class B : public virtual W { /* ... */ };
class C : public A, public B, public virtual W { /* ... */ };
```

In this case there is only one object of class `W` in class `C`.

Constructing the tables for virtual function calls can get quite complicated when virtual base classes are used. However, virtual functions work as usual by choosing the version from the most derived class in a call:

```
class W {
        // ...
public:
        virtual void f();
        virtual void g();
        virtual void h();
        virtual void k();
        // ...
};

class AW : public virtual W { /* ... */ public: void g(); /* ... */ };
class BW : public virtual W { /* ... */ public: void f(); /* ... */ };
class CW : public AW, public BW, public virtual W {
        // ...
public:
        void h();
        // ...
};

CW* pcw = new CW;

pcw->f();                   // invokes BW::f()
pcw->g();                   // invokes AW::g()
pcw->h();                   // invokes CW::h()
((AW*)pcw)->f();            // invokes BW::f() !!!
```

The reason that `BW::f()` is invoked in the last example is that the only `f()` in an object of class `CW` is the one found in the (shared) sub-object `W`, and that one has been overridden by `B::f()`.

Ambiguities are easily detected at the point where `CW`'s table of virtual functions is constructed. The rule for detecting ambiguities in a class DAG is that all re-definitions of a virtual function from a virtual base class must occur on a single path through the DAG. The example above can be drawn like this:

Figure 1-1: A Directed Acyclic Graph

$$\begin{tikzcd}
& W\{\,f\;g\;h\;k\,\} & \\
AW\{\,g\,\} \arrow[ur] & & BW\{\,f\,\} \arrow[ul] \\
& CW\{\,h\,\} \arrow[ul] \arrow[ur] &
\end{tikzcd}$$

Note that a call "up" through one path of the DAG to a virtual function may result in the call of a function (re-defined) in another path (as happened in the call `((AW*)pcw)->f()` in the example above). In this example, an ambiguity would occur if a function `f()` was added to `AW`. This ambiguity might be resolved by adding a function `f()` to `CW`.

Programming with virtual bases is trickier than programming with non-virtual bases. The problem is to avoid multiple calls of a function in a virtual class when that is not desired. Here is a possible style:

```
class W {
        // ...
protected:
        _f() { my stuff }
        // ...
public:
        f() { _f(); }
        // ...
};
```

Each class provides a protected function doing "its own stuff," `_f()`, for use by derived classes and a public function `f()` as the interface for use by the "general public."

```
class A : public virtual W {
        // ...
protected:
        _f() { my stuff }
        // ...
public:
        f() { _f(); W::_f(); }
        // ...
};
```

A derived class `f()` does its "own stuff" by calling `_f()` and its base classes' "own stuff" by calling their `_f()`s.

```
class B : public virtual W  {
        // ...
protected:
        _f() { my stuff }
        // ...
public:
        f() { _f(); W::_f(); }
        // ...
};
```

In particular, this style enables a class that is (indirectly) derived twice from a class `W` to call `W::f()` once only:

```
class C : public A, public B, public virtual W {
        // ...
protected:
        _f() { my stuff }
        // ...
public:
        f() { _f(); A::_f(); B::_f(); W::_f(); }
        // ...
};
```

Method combination schemes, such as the ones found in Lisp systems with multiple inheritance, were considered as a way of reducing the amount of code a programmer needed to write in cases like the one above. However, none of these schemes appeared to be sufficiently simple, general, and efficient enough to warrant the complexity it would add to C++.

As described in Chapter 5 a virtual function call is about as efficient as a normal function call — even in the case of multiple inheritance. The added cost is 5 to 6 memory references per call. This compares with the 3 to 4 extra memory references incurred by a virtual function call in a C++ compiler providing only single inheritance. The multiple inheritance scheme currently used causes an increase of about 50% in the size of the tables used to implement the virtual functions compared with the older single inheritance implementation. To offset that, the multiple inheritance implementation optimizes away quite a few spurious tables generated by the older single-inheritance implementations so that the memory requirement of a program using virtual functions actually decreases in most cases.

It would have been nice if there had been absolutely no added cost for the multiple inheritance scheme when only single inheritance is used. Such schemes exist, but involve the use of tricks that cannot be done by a C++ compiler generating C.

Base and Member Initialization

The syntax for initializing base classes and members has been extended to cope with multiple inheritance and the order of initialization has been more precisely defined. Leaving the initialization order unspecified in the original definition of C++ gave an unnecessary degree of freedom to language implementors at the expense of the users. In most cases, the order of initialization of members doesn't matter and in most cases where it does matter, the order dependency is an indication of bad design. In a few cases, however, the programmer absolutely needs control of the order of initialization. For example, consider transmitting objects between machines. An object must be re-constructed by a receiver in exactly the reverse order in which it was decomposed for transmission by a sender. This cannot be guaranteed for objects communicated between programs compiled by compilers from different suppliers unless the language specifies the order of construction.

Consider:

```
class A { public: A(int); A(); /* ... */ };
class B { public: B(int); B(); /* ... */ };


class C : public A, public B {
        const a;
        int& b;
public:
        C(int&);
};
```

In a constructor the sub-objects representing base classes can be referred to by their class names:

```
C::C(int& rr) : A(1), B(2), a(3), b(rr) { /* ... */ }
```

The initialization takes place in the order of declaration in the class with base classes initialized before members[3], so the initialization order for class `C` is `A`, `B`, `a`, `b`. This order is independent of the order of explicit initializers so

```
C::C(int& rr) : b(rr), B(2), a(3), A(1) { /* ... */ }
```

also initializes in the declaration order `A`, `B`, `a`, `b`.

The reason for ignoring the order of initializers is to preserve the usual FIFO ordering of constructor and destructor calls. Allowing two constructors to use different orders of initialization of bases and members would constrain implementations to use more dynamic and more expensive strategies.

Using the base class name explicitly clarifies even the case of single inheritance without member initialization:

```
class vector {
        // ...
public:
        vector(int);
        // ...
};


class vec : public vector {
        // ...
public:
        vec(int,int);
        // ...
};
```

It is reasonably clear even to novices what is going on here:

```
vec::vec(int low, int high) : vector(high-low-1) { /* ... */ }
```

On the other hand, this version:

```
vec::vec(int low, int high) : (high-low-1) { /* ... */ }
```

has caused much confusion over the years. The old-style base class initializer is of course still accepted. It can be used only in the single inheritance case since it is ambiguous otherwise.

A virtual base is constructed before any of its derived classes. Virtual bases are constructed before any non-virtual bases and in the order they appear on a depth-first left-to-right traversal of the inheritance DAG. This rule applies recursively for virtual bases of virtual bases.

A virtual base is initialized by the "most derived" class of which it is a base. For example:

```
class V { public: V(); V(int); /* ... */ };
class A : public virtual V { public: A(); A(int); /* ... */ };
class B : public virtual V { public: B(); B(int); /* ... */ };
class C : public A, public B { public: C(); C(int); /* ... */ };


A::A(int i) : V(i) { /* ... */ }
B::B(int i) { /* ... */ }
C::C(int i) { /* ... */ }


        V v(1);// use V(int)
        A a(2);// use V(int)
        B b(3);// use V()
        C c(4);// use V()
```

The order of destructor calls is defined to be the reverse order of appearance in the class declaration (members before bases). There is no way for the programmer to control this order – except by the declaration order. A virtual base is destroyed after all of its derived classes.

It might be worth mentioning that virtual destructors are (and always have been) allowed:

```
struct B { /* ... */ virtual ~B(); };

struct D : B { ~D(); };


void g() {
        B* p = new D;
        delete p;// D::~D() is called
}
```

The word `virtual` was chosen for virtual base classes because of some rather vague conceptual similarities to virtual functions and to avoid introducing yet another keyword.

Abstract Classes

One of the purposes of static type checking is to detect mistakes and inconsistencies before a program is run. It was noted that a significant class of detectable errors was escaping C++'s checking. To add insult to injury, the language actually forced programmers to write extra code and generate larger programs to make this happen.

Consider the classic "shape" example. Here, we must first declare a class `shape` to represent the general concept of a shape. This class needs two virtual functions `rotate()` and `draw()`. Naturally, there can be no objects of class shape, only objects of specific shapes. Unfortunately C++ did not provide a way of expressing this simple notion.

The C++ rules specify that virtual functions, such as `rotate()` and `draw()`, must be defined in the class in which they are first declared. The reason for this requirement is to ensure that traditional linkers can be used to link C++ programs and to ensure that it is not possible to call a virtual function that has not been defined. So the programmer writes something like this:

```
class shape {
        point center;
        color col;
        // ...
public:
        where() { return center; }
        move(point p) { center=p; draw(); }
        virtual void rotate(int) { error("cannot rotate"); abort(); }
        virtual void draw() { error("cannot draw"); abort(); }
        // ...
};
```

This ensures that innocent errors such as forgetting to define a `draw()` function for a class derived from `shape` and silly errors such as creating a "plain" `shape` and attempting to use it cause run time errors. Even when such errors are not made, memory can easily get cluttered with unnecessary virtual tables for classes such as `shape` and with functions that are never called, such as `draw()` and `rotate()`. The overhead for this can be noticeable.

The solution is simply to allow the user to say that a virtual function does not have a definition; that is, that it is a "pure virtual function." This is done by an initializer `=0`:

```
class shape {
        point center;
        color col;
        // ...
public:
        where() { return center; }
        move(point p) { center=point; draw(); }
        virtual void rotate(int) = 0;// pure virtual function
        virtual void draw() = 0;// pure virtual function
        // ...
};
```

A class with one or more pure virtual functions is an abstract class. An abstract class can only be used as a base for another class. In particular, it is not possible to create objects of an abstract class. A class derived from an abstract class must either define the pure virtual functions from its base or again declare them to be pure virtual functions.

The notion of pure virtual functions was chosen over the idea of explicitly declaring a class to be abstract because the selective definition of functions is much more flexible.

Static Member Functions

A static data member of a class is a member for which there is only one copy rather than one per object and which can be accessed without referring to any particular object of the class it is a member of. The reason for using static members is to reduce the number of global names, to make obvious which static objects logically belong to which class, and to be able to apply access control to their names. This is a boon for library providers since it avoids polluting the global name space and thereby allows easier writing of library code and safer use of multiple libraries. These reasons apply for functions as well as for objects. In fact, *most* of the names a library provider wants local are function names. It was also observed that non-portable code, such as

```
((X*)0)->f();
```

was used to simulate static member functions. This trick is a time bomb because sooner or later someone will make an `f()` that is used this way `virtual` and the call will fail horribly because there is no `X` object at address zero. Even where `f()` is not virtual such calls will fail under some implementations of dynamic linking.

A static member function is a member so that its name is in the class scope and the usual access control rules apply. A static member function is not associated with any particular object and need not be called using the special member function syntax. For example:

```
class X {
        int mem;
public:
        static void f(int,X*);
};


void g()
{
        X obj;
        f(1,&obj);              // error (unless there really is
                                // a global function f())
        X::f(1,&obj);           // fine
        obj.f(1,&obj);          // also fine
}
```

Since a static member function isn't called for a particular object it has no `this` pointer and cannot access members without explicitly specifying an object. For example:

```
void X::f(int i, X* p)
{
        mem = i;                // error: which mem?
        p->mem = i;             // fine
}
```

`const` Member Functions

Consider this example:

```
class s {
        int aa;
public:
        void mutate() { aa++; }
        int value() { return aa; }
};


void g()
{
        s o1;
        const s o2;
        o1.mutate();
        o2.mutate();
        int i = o1.value() + o2.value();
}
```

It seems clear that the call `o2.mutate()` ought to fail since `o2` is a `const`.

The reason this rule until now has not been enforced is simply that there was no way of distinguishing a member function that may be invoked on a `const` object from one that may not. In general, the compiler cannot deduce which functions will change the value of an object. For example, had `mutate()` been defined in a separately compiled source file the compiler would not have been able to detect the problem at compile time.

The solution to this has two parts. First `const` is enforced so that "ordinary" member functions cannot be called for a `const` object. Then we introduce the notion of a `const` member function, that is, a member function that may be called for all objects including `const` objects. For example:

```
class X {
        int aa;
public:
        void mutate() { aa++; }
        int value() const { return aa; }
};
```

Now `X::value()` is guaranteed not to change the value of an object and can be used on a `const` object whereas `X::mutate()` can only be called for non-`const` objects:

```
int g()
{
        X o1;
        const X o2;
        o1.mutate();        // fine
        o2.mutate();        // error
        return o1.value() + o2.value(); // fine
}
```

In a `const` member function of `X` the `this` pointer points to a `const X`. This ensures that non-devious attempts to modify the value of an object through a `const` member will be caught:

```
class X {
        int a;
        void cheat() const { a++; }          // error
};
```

Note that the use of `const` as a suffix to `()` is consistent with the use of `const` as a suffix to `*`.

Initialization of `static` Members

A `static` data member of a class must be defined somewhere. The `static` declaration in the class declaration is only a declaration and does not set aside storage or provide an initializer.

This is a change from the original C++ definition of `static` members, which relied on implicit definition of `static` members and on implicit initialization of such members to `0`. Unfortunately, this style of initialization cannot be used for objects of all types. In particular, objects of classes with constructors cannot be initialized this way. Furthermore, this style of initialization relied on linker features that are not universally available. Fortunately, in the implementations where this used to work it will continue to work for some time, but conversion to the stricter style described here is strongly recommended.

Here is an example:

```
class X {
        static int i;
        int j;
        X(int);
        int read();
};


class Y {
        static X a;
        int b;
        Y(int);
        int read();
};
```

Now `X::i` and `Y::a` have been declared and can be referred to, but somewhere definitions must be provided. The natural place for such definitions is with the definitions of the class member functions. For example:

```
// file X.c:
X::X(int jj) { j = jj; }
int X::read() { return j; }
int X::i = 3;


// file Y.c:
Y::Y(int bb) { b = bb; }
int Y::read() { return b; }
X Y::a = 7;
```

Pointers to Members

As mentioned in *The C++ Programming Language*, it was an obvious deficiency that there was no way of expressing the concept of a pointer to a member of a class in C++. This lead to the need to "cheat" the type system in cases, such as error handling, where pointers to functions are traditionally used. Consider this example:

```
struct S {
        int mf(char*);
};
```

The structure `S` is declared to be a (trivial) type for which the member function `mf()` is declared. Given a variable of type `S` the function `mf()` can be called:

```
S a;
int i = a.mf("hello");
```

The question is *"What is the type of* `mf()` *?"*

The equivalent type of a non-member function

```
int f(char*);
```

is

```
int (char*)
```

and a pointer to such a function is of type

```
int (*)(char*)
```

Such pointers to "normal" functions are declared and used like this:

```
int f(char*);                  // declare function
int (*pf)(char*) = &f;         // declare and initialize pointer to function
int i = (*pf)("hello");        // call function through pointer
```

A similar syntax is introduced for pointers to members of a specific class. In a definition `mf()` appears as:

```
int S::mf(char*)
```

The type of `S::mf` is:

```
int S:: (char*)
```

that is, "member of `S` that is a function taking a `char*` argument and returning an `int`." A pointer to such a function is of type:

```
int (S::*)(char*)
```

That is, the notation for pointer to member of class `S` is `S::*`. We can now write:

```
            // declare and initialize pointer to member function
int (S::*pmf)(char*) = &S::mf;

S a;
            // call function through pointer for the object ''a''
int i = (a.*pmf)("hello");
```

The syntax isn't exactly pretty, but neither is the C syntax it is modeled on.

A pointer to member function can also be called given a pointer to an object:

```
S* p;
            // call function through pointer for the object ''*p'':
int i = (p->*pmf)("hello");
```

In this case, we might have to handle virtual functions:

```
struct B {
        virtual f();
};

struct D : B {
        f();
};


int ff(B* pb, int (B::*pbf)())
{
        return (pb->*pbf)();
};

void gg()
{
        D dd;
        int i = ff(&dd, &B::f);
}
```

This causes a call of `D::f()`. Naturally, the implementation involves a lookup in `dd`'s table of virtual functions exactly as a call to a virtual function that is identified by name rather than by a pointer. The overhead compared to a "normal function call" is the usual about five memory references (dependent on the machine architecture).

It is also possible to declare and use pointers to members that are not functions:

```
struct S {
        int mem;
};

int S::* psm = &S::mem;


void f(S* ps)
{
        ps->*psm = 2;
}

void g()
{
        S a;
        f(&a);
}
```

This is a complicated way of assigning `2` to `a.mem`.

User-Defined Free Store Management

C++ provides the operators `new` and `delete` to allocate memory on the free store and to release store allocated this way for reuse. Occasionally a user needs a finer-grained control of allocation and deallocation. The first section below shows "the bad old way" of doing this and the following sections shows how the usual scope and overloaded function resolution mechanisms can be exploited to achieve similar effects more elegantly. This means that assignment to `this` is an anachronism and will be removed from the implementations of C++ after a decent interval. This will allow the type of `this` in a member function of class `X` to be changed to `X *const`.

Assignment to `this`

If a user wanted to take over allocation of objects of a class `X` the only way used to be to assign to `this` on each path through every constructor for `X`. Similarly, the user could take control of deallocation by assigning to `this` in a destructor. This is a very powerful and general mechanism. It is also non-obvious, error prone, repetitive, too subtle when derived classes are used, and essentially unmanageable when multiple inheritance is used. For example:

```
class X {
        int on_free_store;
        // ...
public:
        X();
        X(int i);
        ~X();
        // ...
}
```

Every constructor needs code to determine when to use the user-defined allocation strategy:

```
X::X() {
        if (this == 0) {        // 'new' used
                this = myalloc(sizeof(X));
                on_free_store = 1;
        }
        else {                  // static, automatic, or member of aggregate
                this = this;    // forget this assignment at your peril
                on_free_store = 0;
        }
        // initialize
}
```

The assignments to `this` are "magic" in that they suppress the usual compiler generated allocation code.

Similarly, the destructor needs code to determine when to use the user-defined de-allocation strategy and use an assignment to `this` to indicate that it has taken control over deallocation:

```
X::~X() {
        // cleanup
        if (on_free_store) {
                myfree(this);
                this = 0;     // forget this assignment at your peril
        }
}
```

This user-defined allocation and de-allocation strategy isn't inherited by derived classes in the usual way.

The fundamental problem with the "assign to `this`" approach to user-controlled memory management is that initialization and memory management code are intertwined in an ad hoc manner. In particular, this implies that the language cannot provide any help with these critical activities.

Class-Specific Free Store Management

The alternative is to overload the allocation function `operator new()` and the deallocation function `operator delete()` for a class `X`:

```
class X {
        // ...
public:
        void* operator new(size_t sz) { return myalloc(sz); }
        void operator delete(X* p) { myfree(p); }

        X() { /* initialize */ }
        X(int i) { /* initialize */ }

        ~X() { /* cleanup */ }

        // ...
};
```

The type `size_t` is an implementation defined integral type used to hold object sizes[4]. It is the type of the result of `sizeof`.

Now `X::operator new()` will be used instead of the global `operator new()` for objects of class `X`. Note that this does not affect other uses of operator `new` within the scope of `X`:

```
void* X::operator new(size_t s)
{
        void* p = new char[s];  // global operator new as usual
        //...
        return p;
}


void X::operator delete(X* p)
{
        //...
        delete (void*) p;       // global operator delete as usual
}
```

When the new operator is used to create an object of class X, operator new() is found by a lookup starting in X's scope so that X::operator new() is preferred over a global ::operator new().

Inheritance of operator new()

The usual rules for inheritance apply:

```
class Y : public X              // objects of class Y are also allocated
{                               // using X::operator new
        // ...
};
```

This is the reason X::operator new() needs an argument specifying the amount of store to be allocated; sizeof(Y) is typically different from sizeof(X). Naturally, a class that is never a base class need not use the size argument:

```
void* Z::operator new(size_t) { return next_free_Z(); }
```

This optimization should not be used unless the programmer is perfectly sure that Z is never used as a base class because if it is disaster will happen.

An operator new(), be it local or global, is used only for free store allocation so

```
X a1;                           // allocated statically

void f()
{
        X a;                    // allocated on the stack
        X v[10];                // allocated on the stack
}
```

does not involve any operator new(). Instead, store is allocated statically and on the stack.

X::operator new() is only used for individual objects of class X (and objects of classes derived from class X that do not have their own operator new()) so

```
X* p = new X[10];
```

does not involve X::operator new() because X[10] is an array.

Like the global operator new(), X::operator new() returns a void*. This indicates that it returns uninitialized memory. It is the job of the compiler to ensure that the memory returned by this function is converted to the proper type and — if necessary — initialized using the appropriate constructor. This is exactly what happens for the global operator new().

X::operator new() and X::operator delete() are static member functions. In particular, they have no this pointer. This reflects the fact that X::operator new() is called before constructors so that initialization has not yet happened and X::operator delete() is called after the destructor so that the memory no longer holds a valid object of class X.

Overloading operator new()

Like other functions, operator new() can be overloaded. Every operator new() must return a void* and take a size_t as its first argument. For example:

```
void* operator new(size_t sz);    // the usual allocator

void* operator new(size_t sz, heap* h)// allocate from heap 'h'
{
        return h->allocate(sz);
}

void* operator new(size_t, void* p)// place object at 'p'
{
        return p;
}
```

The size argument is implicitly provided when operator new is used. Subsequent arguments must be explicitly provided by the user. The notation used to supply these additional arguments is an argument list placed immediately after the new operator itself:

```
static char buf [sizeof(X)];       // static buffer

class heap {
        // ...
};

heap h1;


f() {
        X* p1 = new X;              // use the default allocator
                                    // operator new(size_t sz):
                                    // operator new(sizeof(X))


        X* p3 = new(&h1) X;         // use h1's allocator
                                    // operator new(size_t sz, heap* h):
                                    // operator new(sizeof(X),&h1)

        X* p2 = new(buf) X;         // explicit allocation in 'buf'
                                    // operator new(size_t, void* p):
                                    // operator new(sizeof(X),buf)
}
```

Note that the explicit arguments go after the new operator but before the type. Arguments after the type go to the constructor as ever. For example:

```
class Y {
        void* operator new(size_t, const char*);
        Y(const char*);
};

Y* p = new("string for the allocator") Y("string for the constructor");
```

Controlling Deallocation

Where many different operator new() functions are used one might imagine that one would need many different and matching operator delete() functions. This would, however, be quite inconvenient and often unmanageable. The fundamental difference between creation and deletion of objects is that at the point of creation the programmer knows just about everything worth knowing about the object whereas at the point of deletion the programmer holds only a pointer to the object. This pointer may not even give the exact type of the object, but only a base class type. It will therefore typically be unreasonable to require the programmer writing a delete to choose among several variants[5].

Consider a class with two allocation functions and a single deallocation function that chooses the proper way of deallocating based on information left in the object by the allocators:

```
class X {
        enum { somehow, other_way } which_allocator;

        void* operator new(size_t sz)
                {       void* p = allocate_somehow();
                        ((X*)p)->which_allocator = somehow;
                        return p;
                }

        void* operator new(size_t sz , int i)
                {       void* p = allocate_some_other_way();
                        ((X*)p)->which_allocator = other_way;
                        return p;
                }

        void operator delete(void*);
        // ...
};
```

Here `operator delete()` can look at the information left behind in the object by the `operator new()` used and deallocate appropriately:

```
void X::operator delete(void* p)
{
        switch (((X*)p)->which_allocator) {
        case somehow:
                deallocate_somehow();
                break;
        case other_way:
                deallocate_some_other_way();
                break;
        default:
                /* something is funny */
        }
}
```

Since `operator new()` and `operator delete()` are static member functions they need to cast their "object pointers" to use member names. Furthermore, these functions will be invoked only by explicit use of operators `new` and `delete`. This implies that `X::which_allocator` is not initialized for automatic objects so in that case it may have an arbitrary value. In particular, the default case in `X::operator delete()` might occur if someone tried to `delete` an automatic (on the stack) object.

Where (as will often be the case) the rest of the member functions of X have no need for examining the information stored by allocators for use by the deallocator this information can be placed in storage outside the object proper ("in the container itself") thus decreasing the memory requirement for automatic and static objects of class X. This is exactly the kind of game played by "ordinary" allocators such as the C malloc() for managing free store.

The example of the use of assignment to this above contains code that depends on knowing whether the object was allocated by new or not. Given local allocators and deallocators, it is usually neither wise nor necessary to do so. However, in a hurry or under serious compatibility constraints, one might use a technique like this:

```
class X {
        static X* last_X;
        int on_free_store;
        // ...

        X();

        void* operator new(long s)
        {
                return last_X = allocate_somehow();
        }

        // ...
};


X::X()
{
        if (this == last_X) { // on free store
                on_free_store = 1;
        }
        else {                  // static or automatic or member of aggregate
                on_free_store = 0;
        }
        // ...
}
```

Note that there is no simple and implementation independent way of determining that an object is allocated on the stack. There never was.

Placement of Objects

For ordinary functions it is possible to specifically call a non-member version of the function by prefixing a call with the scope resolution operator `::`. For example,

```
::open(filename,"rw");
```

calls the global `open()`. Prefixing a use of the `new` operator with `::` has the same effect for `operator new()`; that is,

```
X* p = ::new X;
```

uses a global `operator new()` even if a local `X::operator new()` has been defined. This is useful for placing objects at specific addresses (to cope with memory mapped I/O, etc.) and for implementing container classes that manage storage for the objects they maintain. Using `::` ensures that local allocation functions are not used and the argument(s) specified for `new` allows selection among several global `operator new()` functions. For example:

```
// place object at address p:
void* operator new(size_t, void* p) { return p; }

char buf [sizeof(X)];                       // static buffer

f()
{
        X* p = ::new(buf) X;                // explicit allocation in 'buf'
        p = ::new((void*)0777) X;           // place an X at address 0777
}
```

Naturally, for most classes the `::` will be redundant since most classes do not define their own allocators. The notation `:: delete` can be used similarly to ensure use of a global deallocator.

Memory Exhaustion

Occasionally, an allocator fails to find memory that it can return to its caller. If the allocator must return in this case, it should return the value `0`. A constructor will return immediately upon finding itself called with `this==0` and the complete `new` expression will yield the value `0`. In the absence of more elegant error handling schemes, this enables critical software to defend itself against allocation problems. For example:

```
void f()
{
        X* p = new X;
        if (p == 0) { /* handle allocation error */ }
        // use p
}
```

The use of a `new_handler` can make most such checks unnecessary.

Explicit Calls of Destructors

Where an object is explicitly "placed" at a specific address or in some other way allocated so that no standard deallocator can be used, there might still be a need to destroy the object. This can be done by an explicit call of the destructor:

```
p->X::~X();
```

The fully qualified form of the destructor's name must be used to avoid potential parsing ambiguities. This requirement also alerts the user that something unusual is going on. After the call of the destructor, `p` no longer points to a valid object of class `X`.

Size Argument to `operator delete()`

Like `X::operator new()`, `X::operator delete()` can be overloaded, but since there is no mechanism for the user to supply arguments to a deallocation function this overloading simply presents the programmer with a way of using the information available in the compiler. `X::operator delete()` can have two forms (only):

```
class X {
        void operator delete(void* p);
        void operator delete(void* p, size_t sz);
        // ...
};
```

If the second form is present it will be preferred by the compiler and the second argument will be the size of the object to the best of the compiler's knowledge. This allows a base class to provide memory management services for derived classes:

```
class X {
        void* operator new(size_t sz);
        void operator delete(void* p, size_t sz);

        virtual ~X();
        // ...
};
```

The use of a virtual destructor is crucial for getting the size right in cases where a user deletes an object of a derived class through a pointer to the base class:

```
class Y : public X {
        // ...
        ~Y();
};

X* p = new Y;
delete p;
```

Assignment and Initialization

C++ originally had assignment and initialization default defined as bitwise copy of an object. This caused problems when an object of a class with assignment was used as a member of a class that did not have assignment defined:

```
class X {
        // ...
public:
        X& operator=(const X&);
        // ...
};


class Y {
        X a;
        // ...
};


void f()
{
        Y y1, y2;
        // ...
        y1 = y2;
}
```

Assuming that assignment was not defined for `Y`, `y2.a` is copied into `y1.a` with a bitwise copy. This invariably turns out to be an error and the programmer has to add an assignment operator to class `Y`:

```
class Y {
        X a;
        // ...
        const Y& operator=(const Y& arg)
        {
                a = arg.a;
                // ...
        }
};
```

To cope with this problem in general, assignment in C++ is now defined as memberwise assignment of non-static members and base class objects[6]. Naturally, this rule applies recursively until a member of a built-in type is found. This implies that for a class `X`, `X(const X&)` and `const X& X::operator=(const X&)` will be supplied where necessary by the compiler, as has always been the case for `X::X()` and `X::~X()`. In principle every class `X` has `X::X()`, `X::X(const X&)`, and `X::operator=(const X&)` defined. In particular, defining a constructor `X::X(T)` where `T` isn't a variant of `X&` does not affect the fact that `X::X(const X&)` is defined. Similarly, defining `X::operator=(T)` where `T` isn't a variant of `X&` does not affect the fact that X::operator=(const X&) is defined.

To avoid nasty inconsistencies between the predefined operator=() functions and user defined operator=() functions, operator=() must be a member function. Global assignment functions, such as ::operator(X&,X&) are anachronisms and will be disallowed after a decent interval.

Note that since access controls are correctly applied to both implicit and explicit copy operations we actually have a way of prohibiting assignment of objects of a given class X:

```
class X {
        // Objects of class X cannot be copied
        // except by members of X
        void operator=(X&);
        X(X&);
        // ...
public:
        X(int);
        // ...
};


void f() {
        X a(1);
        X b = a;                // error: X::X(X&) private
        b = a;                  // error: X::operator=(X&) private
}
```

The automatic creation of X::X(const X&) and X::operator=(const X&) has interesting implications on the legality of some assignment operations. Note that if X is a public base class of Y then a Y object is a legal argument for a function that requires an X&. For example:

```
class X { public: int aa; };
class Y : public X { public: int bb; };


void f() {
        X xx;
        Y yy;
        xx = yy;                // ok: a Y is an X
                                //     xx==yy; means xx.operator=((X&)yy);
                                //     and is optimized to xx.aa = yy.aa
}
```

Defining assignment as memberwise assignment implies that operator=() isn't inherited in the ordinary manner. Instead, the appropriate assignment operator is — if necessary — generated for each class. This implies that the "opposite" assignment of an object of a base class to a variable of a derived class is illegal as ever:

```
void f() {
        X xx;
        Y yy;
        yy = xx;                // error: an X is not a Y
}
```

The extension of the assignment semantics to allow assignment of an object of a derived class to a variable of a public base class had been repeatedly requested by users. The direct connection to the recursive memberwise assignment semantics became clear only through work on the two apparently independent problems.

Operator ->

Until now -> has been one of the few operators a programmer couldn't define. This made it hard to create classes of objects intended to behave like "smart pointers." When overloading, -> is considered a unary operator (of its left hand operand) and -> is reapplied to the result of executing `operator->()`. Hence the return type of an `operator->()` function must be a pointer to a class or an object of a class for which `operator->()` is defined. For example:

```
struct Y { int m; };

class X {
        Y* p;
        // ...
        Y* operator->() {
                if (p == 0) {
                        // initialize p
                }
                else {
                        // check p
                }
                return p;
        }
        // ...
};
```

Here, class `X` is defined so that objects of type `X` act as pointers to objects of class `Y`, except that some suitable computation is performed on each access.

```
void f(X x, X& xr, X* xp)
{
        x->m;                   // x.p->m
        xr->m;                  // xr.p->m
        xp->m;                  // error: X does not have a member m
}
```

Like `operator=()`, `operator[]()`, and `operator()()`, `operator->()` must be a member function (unlike `operator+()`, `operator-()`, `operator<()`, etc., which are often most useful as `friend` functions).

The dot operator still cannot be overloaded.

For ordinary pointers, use of -> is synonymous with some uses of unary `*` and `[]`. For example, for

```
Y* p;
```

it holds that:

```
p->m == (*p).m == p[0].m
```

As usual, no such guarantee is provided for user-defined operators. The equivalence can be provided where desired:

```
class X {
        Y* p;
public:
        Y* operator->() { return p; }
        Y& operator*() { return *p; }
        Y& operator[](int i) { return p[i]; }
};
```

If you provide more than one of these operators it might be wise to provide the equivalence exactly as it is wise to ensure that x+=1 has the same effect as x=x+1 for a simple variable x of some class if +=, =, and + are provided.

The overloading of -> is important to a class of interesting programs, just like overloading `[]`, and not just a minor curiosity. The reason is that *indirection* is a key concept and that overloading -> provides a clean, direct, and efficient way of representing it in a program. Another way of looking at operator -> is to consider it a way of providing C++ with a limited, but very useful, form of *delegation*.

Operator ,

Until now the comma operator , has been one of the few operators a programmer couldn't define. This restriction did not appear to have any purpose so it has been removed. The most obvious use of an overloaded comma operator is list building:

```
class Xlist {
        // ...
public:
        Xlist();
        Xlist(X&);
        Xlist& operator,(X&);
        friend Xlist operator,(X&,X&);
};


void f()
{
        X a,b,c;
        Xlist xl = (a,b,c);     // meaning operator,(a,b).operator,(c)
}
```

If you have a bit of trouble deciding which commas mean what in this example you have found the reason overloading of comma was originally left out.

Initialization of `static` Objects

In C, a static object can only be initialized using a slightly extended form of constant expressions. In C++, it has always been possible to use completely general expressions for the initialization of static class objects. This feature has now been extended to static objects of all types. For example:

```
#include <math.h>

double sqrt2 = sqrt(2);

main()
{
        if (sqrt(2)!=sqrt2) abort();
}
```

Such dynamic initialization is done in declaration order within a file and before the first use of any object or function defined in the file. No order is defined for initialization of objects in different source files except that all static initialization takes place before any dynamic initialization.

Resolutions

This section does not describe additions to C++ but gives answers to questions that have been asked often and do not appear to have clear enough answers in the reference manual of *The C++ Programming Language*. These resolutions involve slight changes compared to earlier rules. This was done to bring C++ closer to the ANSI C draft.

Function Argument Syntax

Like the C syntax, the C++ syntax for specifying types allows the type `int` to be implicit in some cases. This opens the possibility of ambiguities. In argument declarations, C++ chooses the longest type possible when there appears to be a choice:

```
typedef long I;
f1(const I);        // f1() takes an unnamed 'const long' argument
f2(const i);        // f2() takes a 'const int' argument (called 'i')
```

This rule applies to the `const` and `volatile` specifiers, but not to `unsigned`, `short`, `long`, or `signed`[7]:

```
f3(unsigned int I);           // ok
f4(unsigned I);               // ok: equivalent to f4(unsigned int I);
```

A type cannot contain two basic type specifiers so

```
f5(char I) { I++; }
f6(I I) { I++; }
```

are legal.

Declaration and Expression Syntax

There is an ambiguity in the C++ grammar involving *expression-statements* and *declarations*: An *expression-statement* with a "function style" explicit type conversion as its leftmost sub-expression can be indistinguishable from a *declaration* where the first *declarator* starts with a `(`. For example:

```
T(a);               //declaration or type conversion of 'a'
```

In those cases the *statement* is a *declaration*.

To disambiguate, the whole *statement* may have to be examined to determine if it is an *expression-statement* or a *declaration*. This disambiguates many examples. For example, assume `T` is the name of some type:

```
T(a)->m = 7;                // expression-statement
T(a)++;                     // expression-statement
T(a,5)<<c;                  // expression-statement
T(*d)(double(3));           // expression-statement


T(*e)(int);                 // declaration
T(f)[];                     // declaration
T(g)={ 1,2 };               // declaration
```

The remaining cases are *declarations*. For example:

```
T(a);                       // declaration
T(*b)();                    // declaration
T(c)=7;                     // declaration
T(d),e,f=3;                 // declaration
T(g)(h,2);                  // declaration
```

The disambiguation is purely syntactic; that is, the meaning of the names, beyond whether they are names of types or not, is not used in the disambiguation.

This resolution has two virtues compared to alternatives: it is simple to explain and completely compatible with C. The main snag is that it is not well adapted to simple minded parsers, such as YACC, because the lookahead required to decide what is an *expression-statement* and what is a *declaration* in a statement context is not limited.

However, note that a simple lexical lookahead can help a parser disambiguate most cases. Consider analyzing a *statement*; the troublesome cases look like this:

T (*d-or-e*) *tail*

Here, *d-or-e* must be a *declarator*, an *expression*, or both for the statement to be legal. This implies that *tail* must be a semicolon, something that can follow a parenthesized *declarator* or something that can follow a parenthesized *expression*. That is, an *initializer*, `const`, `volatile`, `(`, or `[` or a postfix or infix operator.

A user can explicitly disambiguate cases that appear obscure. For example:

```
void f()
{
        auto int(*p)();  // explicitly declaration
        (void) int(*p)();// explicitly expression-statement
        0,int(*p)();     // explicitly expression-statement
        (int(*p)());     // explicitly expression-statement
        int(*p)();       // resolved to declaration
}
```

Enumerators

An enumeration is a type. Each enumeration is distinct from all other types. The set of possible values for an enumeration is its set of enumerators. The type of an enumerator is its enumeration. For example:

```
enum wine { red, white, rose, bubbly };
enum beer { ale, bitter, lager, stout };
```

defines two types, each with a distinct set of 4 values.

```
wine w = red;
beer b = bitter;

w = b;              // error, type mismatch: beer assigned to wine
w = stout;          // error, type mismatch: beer assigned to wine
w = 2;              // error, type mismatch: int assigned to wine
```

Each enumerator has an integer value and can be used wherever an integer is required; in such cases the integer value is used:

```
int i = rose        // the value of 'rose' (that is, 2) is used
i = b;              // the value of 'b' is assigned to 'i'
```

This interpretation is stricter than what has been used in C++ until now and stricter than most C dialects. The reason for choosing it was ANSI C's requirement that enumerations be distinct types. Given that, the details follow from C++'s emphasis on type checking and the requirements of consistency to allow overloading, etc. For example:

```
int f(int);
int f(wine);

void g()
{
        f(i);                   // f(int)
        f(w);                   // f(wine)

        f(1);                   // f(int)
        f(white);               // f(wine)

        f(b);                   // f(int), standard conversion
                                //         from beer to int used
}
```

C++'s checking of enumerations is stricter than ANSI C's, in that assignments of integers to enumerations are disallowed. As ever, explicit type conversion can be used:

```
w = wine(257);      /* caveat emptor */
```

An enumerator is entered in the scope in which the enumeration is defined. In this context, a class is considered a scope and the usual access control rules apply. For example:

```
class X {
        enum { x, y, z };
        // ...
public:
        enum { a, b, c };

        f(int i = a) { g(i+x); ... }
        // ...
}


void h() {
        int i = a;              // error: 'X::a' is not in scope
        i = X::a;               // ok
        i = X::x;               // error: 'X::x' is private
}
```

The `const` Specifier

Use of the `const` specifier on a non-local object implies that linkage is *internal* by default; that is, the object declared is local to the compilation in which it occurs. To give it external linkage it must be explicitly declared `extern`.

Similarly, `inline` implies that linkage is *internal* by default.

External linkage can be obtained by explicit declaration:

```
extern const double g;
const double g = 9.81;

extern inline f(int);
inline f(int i) { return i+c; }
```

Function Types

It is possible to define function types that can be used exactly like other types, except that variables of function types cannot be defined — only variables of pointer to function types:

```
typedef int F(char*);           // function taking a char* argument
                                // and returning an int
F* pf;                          // pointer to such function
F f;                            // error: no variables of function type allowed
```

Function types can be useful in friend declarations. Here is an example from the C++ task system:

```
class task : public scheduler {
      friend SIG_FUNC_TYP sig_func; // the type of a function must be specified
                                    // in a friend function declaration
      // ...
}
```

The reason to use a typedef in the friend declaration sig_func and not simply to write the type directly is that the type of signal() is system dependent:

```
// BSD signal.h:
typedef void SIG_FUNC_TYP(int, int, sigcontext*);


// 9th edition signal.h:
typedef void SIG_FUNC_TYP(int);
```

Using the typedef allows the system dependencies to be localized where they belong: in the header files defining the system interface.

Lvalues

Note that the default definition of assignment of an X as a call of

```
X& operator=(const X&)
```

makes assignment of Xs produce an lvalue. For uniformity, this rule has been extended to assignments of built-in types. By implication, +=, -=, *=, etc., now also produce lvalues. So — again by implication — does prefix ++ and -- (but not the postfix versions of these operators).

In addition, the comma and ?: can also produce lvalues. The result of a comma operation is an lvalue if its second operand is. The result of a ?: operator is an lvalue provided both its second and third operands are and provided they have exactly the same type.

Multiple Name Spaces

C provides a separate name space for structure tags whereas C++ places type names in the same name space as other names. This gives important notational conveniences to the C++ programmer but severe headaches to people managing header files in mixed C/C++ environments. For example:

```
struct stat {
        // ...
};

extern struct stat(int, struct stat *);
```

was not legal C++ though early implementations accepted it as a compatibility hack. The experience has been that trying to impose the '"pure C++" single name space solution (thus outlawing examples such as the one above) has caused too much confusion and too much inconvenience to too many users. Consequently, a slightly cleaned up version of the C/C++ compatibility hack has now become part of C++. This follows the overall principle that where there is a choice between inconveniencing compiler writers and annoying users, the compiler writers should be inconvenienced. It appears that the compromise provided by the rules presented below enables all accepted uses of multiple name spaces in C while preserving the notational convenience of C++ in all cases where C compatibility isn't an essential issue. In particular, every legal C++ program remains legal. The restrictions on the use of constructors and typedef names in connection with the use of multiple name spaces are imposed to prevent some nasty cases of hard to detect ambiguities that would cause trouble for the composition of C++ header files.

A typedef can declare a name to refer to the same type more than once. For example:

```
typedef struct s { /* ... */ } s;
typedef s s;
```

A name `s` can be declared as a type (struct, class, union, enum) *and* as a non-type (function, object, value, etc.) in a single scope. In this case, the name `s` refers to the non-type and `struct s` (or whatever) can be used to refer to the type. The order of declaration does not matter. This rule takes effect only after both declarations of `s` have been seen. For example:

```
struct stat { /* ... */ };
stat a;
void stat(stat* p);
struct stat b;                  // struct is needed to avoid the function name
stat(0);                        // function call


int f(int);
f(1);
struct f { /* ... */ };
struct f a;                     // struct is needed to avoid the function name
```

A name cannot simultaneously refer to two types:

```
struct s { /* ... */ };
typedef int s;                  // error
```

The name of a class with a constructor cannot also simultaneously refer to something else:

```
struct s { s(); /* ... */ };
int s();                        // error


struct t* p;
int t();                        // ok
int i = t();
struct t { t(); /* ... */ }     // error
i = t();
```

If a non-type name s hides a type name s, struct s can be used to refer to the type name. For example:

```
struct s { /* ... */ };
f(int s) { struct s a; s++; }
```

Note: If a type name hides a non-type name the usual scope rules apply:

```
int s;
f()
{
        struct s { /* ... */ }; // new 's' refers to the type
                                // and the global int is hidden
        s a;
}
```

Use of the :: scope resolution operator implies that its argument is a non-type name. For example:

```
int s;
f()
{
        struct s { /* ... */ };
        s a;
        ::s = a;
}
```

Function Declaration Syntax

To ease use of common C++ and ANSI C header files, void may be used to indicate that a function takes no arguments:

```
extern int f(void);            // same as ''extern int f();''
```

Conclusions

C++ is holding up nicely under the strain of large scale use in a diverse range of application areas. The extensions added so far have been have all been relatively easy to integrate into the C++ type system. The C syntax, especially the C declarator syntax, has consistently caused much greater problems that the C semantics; it remains barely manageable. The stringent requirements of compatibility and maintenance of the usual run-time and space efficiencies did not constrain the design of the new features noticeably. Except for the introduction of the keywords catch, private, protected, signed, template, and volatile, the extensions described here are upward compatible. Users will find, however, that type-safe linkage, improved enforcement of const, and improved handling of ambiguities will force modification of some programs by detecting previously uncaught errors.

Footnotes

1. Surprisingly, giving character constants type `char` does not cause incompatibilities with C where they have type `int`. Except for the pathological example `sizeof('a')`, every construct that can be expressed in both C and C++ gives the same result. The reason for the surprising compatibility is that even though character constants have type `int` in C, the rules for determining the values of such constants involves the standard conversion from `char` to `int`.
2. The strategy for dealing with ambiguities in inheritance DAGs is essentially the same as the strategy for dealing with ambiguities in expression evaluation involving overloaded operators and user-defined coercions. Note that the access control mechanism does not affect the ambiguity control mechanism. Had `B::f()` been `private` the call `p->f()` would still be ambiguous.
3. Virtual base classes force a modification to this rule; see below.
4. `operator new()` used to require a `long`; `size_t` was adopted to bring C++ allocation mechanisms into line with ANSI C.
5. The requirement that a programmer must distinguish between `delete p` for an individual object and `delete[n] p` for an array is an unfortunate hack and is mitigated only by the fact that there is nothing that forces a programmer to use such arrays.
6. One could argue that the original definition of C++ was inconsistent in requiring bitwise copy of objects of class `Y`, yet guaranteeing that `X::operator=()` would be applied for copying objects of a class `X`. In this case both guarantees cannot be fulfilled.
7. This resolution involves a slight change compared to earlier rules. This was done to bring this aspect of C++ into line with the ANSI C draft.

2 An Introduction to C++

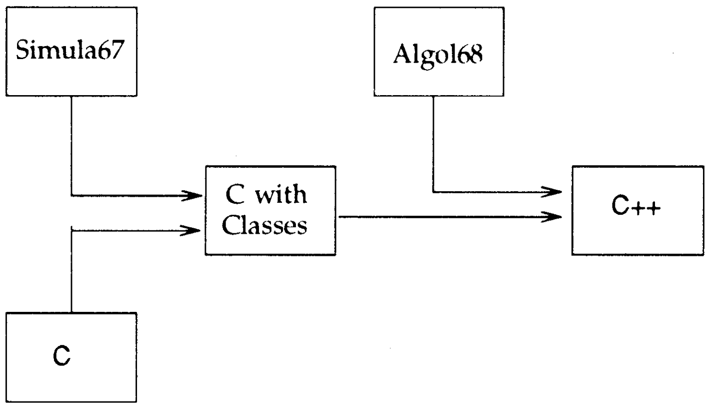
An Introduction to C++

NOTE This chapter is taken directly from a paper by Keith Gorlen.

The C++ programming language was designed and implemented by Bjarne Stroustrup of AT&T Bell Laboratories as a successor to C[1]. It retains compatibility with existing C programs and the efficiency of C. It also adds many powerful new capabilities, making it suitable for a wide range of applications from device drivers to artificial intelligence. C++ will be of interest to UNIX users because of its intimate relation to C and its potential use for building graphical user interfaces to UNIX, for UNIX systems programming, and for supporting large-scale software development under UNIX.

C++ evolved from a dialect of C known as "C with Classes," which was invented in 1980 as a language for writing efficient event-driven simulations. Several key ideas were borrowed from the Simula67 and Algol 68 programming languages. Figure 2-1 shows the heritage of C++.

Figure 2-1: The Heritage of C++



The definitive book on C++ is Bjarne Stroustrup's *The C++ Programming Language*, which gives a detailed description of the language and contains many examples and exercises. It also includes the C++ reference manual, which is a concise, more formal definition of the language.

In this chapter, we'll see how C++ corrects most of the deficiencies of C by offering improved compile-time type checking and support for encapsulation. We'll also introduce you to many of the new features of C++:

- classes
- type checking

- operator and function name overloading
- free store management
- constant types
- references
- inline functions
- derived classes
- virtual functions

We'll present these features in the context of a non-trivial example so that you'll understand the motivation behind them and see how they are typically used.

By the end of the paper, you'll see how proper use of C++ can dramatically increase a programmer's productivity. C++ programs are shorter, clearer, and more likely to be correct from the outset. As a result, they are also easier to debug and to maintain.

We'll conclude the paper by discussing the current status and future of C++.

A C++ Example

The best way to learn about C++ is to write a program in it, and that is what we'll do in the next three sections. Let's start in familiar territory by taking a look at a simple program written in plain old C:

```
main()
{
        int a = 193;
        int b = 456;
        int c = a + b + 47;
        printf("%d\n",c);
}
```

This program declares three integer variables named a, b, and c, initializing a and b to the values 193 and 456, respectively. The integer c is initialized to the result of adding a and b and the constant 47. Finally, the standard C library function printf() is called to print out the value of c. The quoted string %d\n tells how to print the result: %d prints c as a decimal number, and \n adds a newline character. If we compile and execute this program, it prints out the number 696 and exits.

Now suppose we wish to perform a similar calculation, but this time a and b are big numbers, like the U. S. national debt expressed in dollars. Such numbers are too big to be stored as ints on most computers, so if we tried to write int a = 25123654789456 the C compiler (hopefully!) would give us an error message and fail to compile the program. There are many practical applications for big integers, such as cryptography, symbolic algebra, and number theory, where it can be necessary to perform arithmetic on numbers with hundreds or even thousands of digits.

It isn't easy to write a program to deal with these big numbers in ordinary C. Coding and debugging the algorithms that perform arithmetic operations on big integers in C involves a significant amount of work, so we'd want to make them general-purpose. We wouldn't be able to predict how big the numbers might become in advance, so we would have to use a dynamic memory allocator to manage their storage at execution time. We'd need to write a C library of functions for creating, destroying, reading, printing, assigning, and performing basic arithmetic on big integers. These functions would have to have distinctive names such as create_bigint, print_bigint, and add_bigints to avoid confusion with other kinds of data that we might want to create, print, or add in the same program.

Worst of all, programmers wishing to use our big integers would have to know the names of these functions and the rules for calling them. They would have to remember to create and initialize big integers when they needed to use them, and to destroy them when they were finished. Even simple arithmetic expressions would be awkward to write; c = a+b would have to be coded as:

```
assign_bigint(&c,add_bigints(a,b))
```

and there might be problems with handling temporary results calculated during the evaluation of a complex expression. Also, programmers would have to be careful when combining big integers with other data types such as int. They would need to call a function to convert ints to big integers before adding them, for example. Any C program using big integers would be both difficult to write and difficult to read.

In C++, we still must write the code to manage the storage of big integers and functions to perform the same operations on them. The difference is that C++ lets us "package" this code so that using our big integers is as convenient as using the int data type that is built into C. We can, in effect, extend the C++ language by adding our own custom data type, which we'll call BigInt. Notice how similar the example

C program is to this C++ program which performs a similar calculation using `BigInts` instead of `ints`:

```
#include "BigInt.h"
main()
{
        BigInt a =  "25123654789456";
        BigInt b = "456023398798362";
        BigInt c = a + b + 47;
        c.print();/* print the result, c */
        printf("\n");
}
```

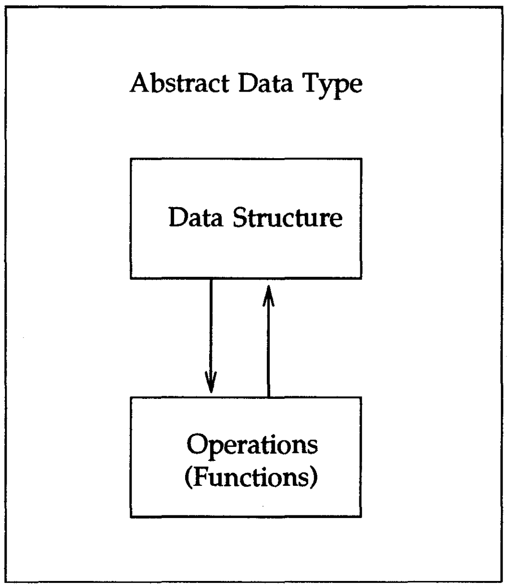
Data Abstraction

This technique of defining new data types that are well-suited to the application to be programmed is known as *data abstraction,* and a data type such as `BigInt` is called an *abstract data type.* Data abstraction is a powerful, general-purpose technique which, when properly used, can result in shorter, more readable, more flexible programs.

Data abstraction is supported by several other modern programming languages such as Ada.

In these languages, and in C++ as well, a programmer can define a new abstract data type by specifying a data structure together with the operations permissible on that data structure, as shown in Figure 2-2.

Figure 2-2: An Abstract Data Type



It is difficult or impossible to practice data abstraction in most other programming languages currently in widespread use, such as BASIC, C, COBOL, FORTRAN, PASCAL, or Modula-2. This is because data abstraction requires special language features not available in these languages. To get an idea of what these features do, let's analyze the example C++ program.

The first three statements in the body of the `main()` program declare three type `BigInt` variables, `a`, `b`, and `c`. The C++ compiler needs to know how to create them — how much space to allocate for them and how to initialize them.

The first and second statements are similar; they initialize the `BigInt` variables `a` and `b` with big integer constants written as character strings containing only digits. To do this the C++ compiler must be able to convert character strings into `BigInt`s.

The third statement is the most complicated. It adds `a`, `b`, and the integer constant 47 and stores the result in `c`. The C++ compiler needs to be able to create a temporary `BigInt` variable to hold the sum of `a` and `b`. Then it must convert the `int` constant 47 into a `BigInt` and add this to the temporary variable. Finally, it must initialize `c` from this temporary `BigInt` variable.

The fourth statement prints `c` on the standard output, and the last statement calls the C library function `printf()` to print a newline character. C programmers are probably familiar with `printf()`, but `c.print()` probably looks a bit strange. It is a call on a special kind of function available in C++ called a *member function*. We'll talk more about this later, but for now just think of it as a function that prints out a variable of type `BigInt`.

Even though there are no more statements in the body of `main()`, the compiler isn't finished yet. It must destroy the `BigInt` variables `a`, `b`, and `c` and any `BigInt` temporaries it may have created before leaving a function, such as `main()`. This is to assure that the storage used by these variables is freed.

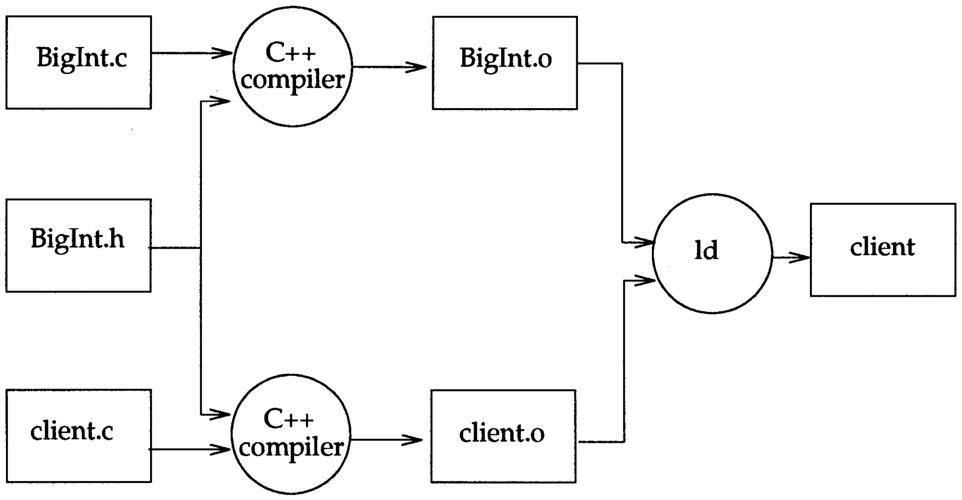
Let's summarize what the C++ compiler needs to know how to do with `BigInts` to compile the example program:

- *create* new instances of `BigInt` variables
- *convert* character strings and integers to `BigInts`
- *initialize* the value of one `BigInt` with that of another `BigInt`
- *add* two `BigInts` together
- *print* `BigInts`
- *destroy* `BigInts` when they are no longer needed

Specifications and Implementations

Where does the C++ compiler obtain this know-how? From the file `BigInt.h`, which is included by the first line of the example program. This file contains the *specification* of our `BigInt` abstract data type. The specification contains the information that programs that *use* an abstract data type need to have to be successfully compiled. The details of *how* the abstract data type works, known as the *implementation*, are kept in another file. In our example, this file is named `BigInt.c`. It is compiled separately, and the object code produced from it is linked with the program that uses the abstract data type, also called the *client* program. Figure 2-3 shows how the specification and implementation of an abstract data type are combined with the source code of a client program to produce an executable program.

Figure 2-3: Combining the specification (BigInt.h) and implementation (BigInt.c) of an abstract data type (BigInt) with the source code of a client program (client.c) to produce an executable program(client).



We separate the code for an abstract data type into a specification part and an implementation part to hide the implementation details from the client. We can then change the implementation and be confident that client programs will continue to work correctly after they are relinked with the modified object code. This is useful when a team of programmers work on a large software project. Once they agree on the specifications for the abstract data types they need, each team member can implement one or more of them independently of the rest of the team.

A well-designed abstract data type also hides its complexity in its implementation, making it as easy as possible for clients to use.

The Specification

Let's take a look at the specification for our `BigInt` data type, contained in the file `BigInt.h`. (Note that in C++, `//`
begins a comment that extends to the end of the line.)

```
class BigInt {
      char* digits;                      // pointer to digit array in free store
      int ndigits;                       // number of digits
public:
      BigInt(const char*);               // constructor function
      BigInt(int);                       // constructor function
      BigInt(const BigInt&);             // initialization constructor function
      BigInt operator+(const BigInt&); // addition operator function
      void print();                      // printing function
      ~BigInt();                         // destructor function
};
```

Much of this code may look odd, but we'll explain it as we cover the features of C++ in the next few sections.

Classes

This is an example of one of the most important features of C++, the `class` declaration, which specifies an abstract data type. It is an extension of something C programmers are probably already familiar with: the `struct` declaration.

The `struct` declaration groups together a number of variables, which may be of different types, into a unit. For example, in C (or in C++) we can write:

```
struct BigInt {
         char* digits;
         int ndigits;
};
```

We can then declare an *instance* of this structure by writing:

```
struct BigInt a;
```

The individual *member variables* of the `struct`, `digits` and `ndigits`, can be accessed using the dot (`.`) operator; for example, `a.digits`, accesses the member variable `digits` of the `struct a`.

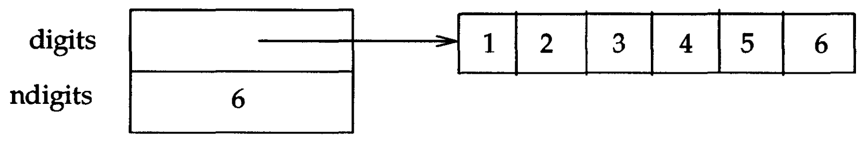
Recall that in C we can also declare a pointer to an instance of a structure:

```
struct BigInt* p;
```

in which case we can access the individual member variables by using the -> operator; for example, `p->digits`.

C++ classes work in a similar manner, and the . and -> operators are used in the same way to access a class's member variables. In our example, class BigInt has two member variables named digits and ndigits. The variable digits points to an array of bytes (chars), allocated from the free storage area, that holds the digits of the big integer, one decimal digit per byte. The digits are ordered beginning with the least significant digit in the first byte of the array. The member variable ndigits contains the number of digits in the integer. Figure 2-4 shows a diagram of this data structure for the number 654321.

Figure 2-4: A diagram of the BigInt data structure for the number 654321



However, the C++ class can do much more than the struct feature of regular C. We'll now look at these extensions in detail.

Encapsulation

In C++, a client program can declare an instance of class BigInt by writing:

```
BigInt a;
```

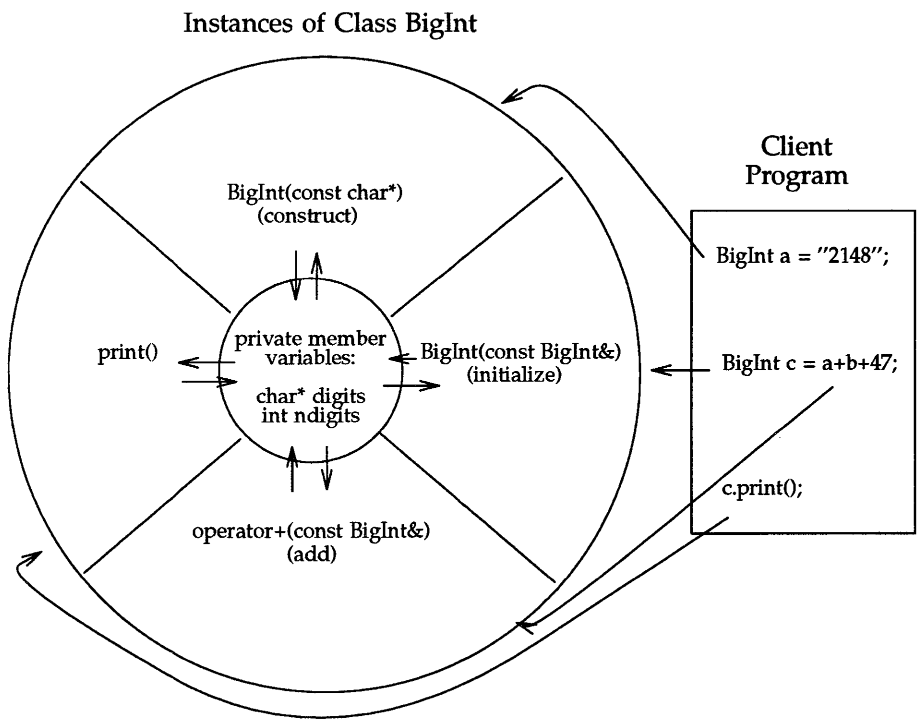
But now we have a potential problem: the client program might try, for example, to use the fact that a.ndigits contains the number of digits in the number a. This would make the client program dependent on the *implementation* of class BigInt — after all, we might wish to change the representation of BigInts to use hexadecimal instead of decimal arithmetic to save storage. We need a way to prevent unauthorized access to the member variables of the instances of a class. C++ provides this by allowing the use of the keyword public: within a class declaration to indicate which members can be accessed by anyone and which have restricted access. Members declared before the public: keyword are *private,* as are digits and ndigits in this example, so C++ will issue an error message if a client program attempts to use them.

Protecting the member variables of a class in this manner is known as *encapsulation.* It is a good programming practice because it enforces the separation between the specification and the implementation of abstract data types that we are trying to achieve, and it helps when debugging programs. For example, if we find that ndigits has the wrong value in some situation, those parts of the program that do not have access to the variable are probably not at fault.

Member Functions

But how does a client program interact with the private member variables of a class? Whereas a `struct` allows only variables to be grouped together, the C++ `class` declaration allows both variables and the functions that operate on them to be grouped. Such functions are called *member functions,* and the private member variables of the instances of a class can be accessed only by the member functions of that class. Thus, a client program can read or modify the values of the private member variables of an instance of a class indirectly, by calling the public member functions of the class, as shown in Figure 2-5.

Figure 2-5: Client programs can access the private member variables of an instance of a class only by calling public member functions of the class.



Our example class `BigInt` has two private member variables, `digits` and `ndigits`, and six public member functions. The declarations of these member functions will look unusual to C programmers for several reasons: the types of the arguments of the functions are listed within parentheses in the function declarations, three of the functions declared have the same name, `BigInt`, and the function names `operator+` and `~BigInt` contain characters normally not allowed in function names.

Function Argument Type Checking

C++ strongly encourages a programmer to declare the types of the arguments of all functions. This makes it possible for C++ to check for inconsistent argument types when a function call is compiled, and can eliminate many bugs at an early stage. For example, the C statement:

```
fprintf("The answer is %d",x);
```

will compile with no problem. However, when this statement is executed the program will abort with a cryptic error message. The problem is that the standard C library function `fprintf()` expects the first argument to be a pointer to the stream to which the output is to be written, not a format string as it is here. On the other hand, in C++ we can declare the argument types of `fprintf()`:

```
extern int fprintf(FILE*, const char*, ...);
```

so the compiler can give us an error message when we try to compile the incorrect function call, noting the discrepancy in the argument types. Conveniently, the argument types for most standard library functions are declared in system header files that you can include in your programs so that you don't have to write all these common declarations yourself.

Function Name Overloading

Listing the types of all of a function's arguments in its declaration has a second benefit: we can define several functions with the same name, as long as each requires a different number and/or type of argument. For example, in C++ we can declare two functions with the name `abs`:

```
int abs(int);
float abs(float);
```

We can then write:

```
x = abs(2);
y = abs(3.14);
```

The first statement will call `abs(int)`, and the second will call `abs(float)` — the C++ compiler knows which `abs` to use because `2` is an `int` and `3.14` is a `float`. When more than one function has the same name like this, the name is said to be *overloaded*. One advantage of overloading is that it eliminates "funny" function names (remember `ABS`, `IABS`, `DABS`, and `CABS` from FORTRAN?). It also leads to more general programs; for example, we can write `copy(x,y)` to copy a `y` to an `x` without having to worry about their types — they might be arrays, or strings, or files — as long as we have written a `copy` function to handle each case.

Calling Member Functions

Getting back to our BigInt example and our discussion of member functions, we can now explain the next-to-last line in our first C++ program which is:

```
        c.print();
```

Member functions are called in a manner analogous to the way member variables are normally accessed in C; that is, by using the . or -> operators. Since c is an instance of class BigInt, the notation c.print() calls the member function print() of class BigInt to print the current value of c. Similarly, if we declared a pointer to a BigInt:

```
        BigInt* p;
```

then the notation p->print() would call the same function. This notation prevents this particular print() from inadvertently being called to operate on anything other than an instance of class BigInt.

In C++, several different classes may all have member functions with the same name, just as in regular C several different structs may all have member variables with the same name. This lets us use simple function names, like print, rather than distinctive names, like print_bigint, without worrying about naming conflicts. We could add a new class, say BigFloat, to a program that also used BigInts, and we could also define print() as a member function of class BigFloat. Our program could contain the statements:

```
        BigInt a = "2934673485419";
        BigFloat x = "874387430.3945798";
        a.print();
        x.print();
```

and the C++ compiler would use the appropriate print() in both cases.

Constructors

As you'll recall, one of the things the C++ compiler needs to know about our BigInt abstract data type is how to create new instances of BigInts. We can tell C++ how we want this done by defining one or more special member functions called *constructors*. A constructor function is one which has the same name as its class. When a client program contains a declaration such as:

```
        BigInt a = "123";
```

the C++ compiler reserves space for the member variables of an instance of class BigInt and calls the constructor function a.BigInt(It is our responsibility as providers of the BigInt data type to write the function BigInt() so that it initializes the instance correctly. In our example, we'll have BigInt(allocate three bytes of dynamic storage, set a.digits to point to this storage, set the three bytes to {3,2,1}, and set a.ndigits to three. This will create an instance of class BigInt named a that is initialized to 123.

If a class has a constructor function, C++ *guarantees* that it will be called to initialize every instance of the class that is created. A user of an abstract data type such as `BigInt` does not have to remember to call an initialization function separately for every `BigInt` declared, thus eliminating a common source of programming errors.

Constructors and Type Conversion

The second thing C++ needs to know is how to convert something that is a character string, such as `25123654789456`, or an integer, such as 47, to a `BigInt`. Constructors are also used for this purpose. When the C++ compiler sees a statement like:

```
BigInt c = a + b + 47;
```

it recognizes that the `int 47` must be converted to a `BigInt` before the addition can be done, and so checks to see if the constructor `BigInt(int)` is declared. If so, it creates a temporary instance of `BigInt` by calling `BigInt(int)` with the argument `47`. If an appropriate constructor is not declared, the statement is flagged as an error. We have defined `BigInt(char*)` and `BigInt(int)` for class `BigInt`, so we may freely use character strings or integers wherever a `BigInt` can be used, and the C++ compiler will automatically call our constructor to do the type conversion. This is an important feature of C++ because it lets us blend our own abstract data types with others and with the fundamental types built into the language.

Constructors and Initialization

The third thing C++ must know how to do is how to initialize a `BigInt` with the value of another `BigInt`, as is required by a statement such as:

```
BigInt c = a + b + 47;
```

The `BigInt c` must be initialized with the value of a temporary `BigInt` that holds the result of the expression `a + b + 47`.

We can control how C++ initializes instances of class `BigInt` by defining the special constructor function `BigInt(const BigInt&)`. In our example, we'll make this constructor allocate storage for the new instance and make a copy of the contents of the argument instance.

Operator Overloading

The fourth thing C++ must be able to do is to add two `BigInt`s. We could just define a member function named `add` to do this, but then writing arithmetic expressions would be awkward. C++ lets us define additional meanings for most of its operators, including `+`, so we can make it mean "add" when applied to `BigInt`s. This is known as *operator overloading*, and is similar to the concept of function name overloading.

Actually, most programmers are already familiar with this idea because the operators of most programming languages, including C, are already overloaded. For example, we can write:

```
int a,b,c;
float x,y,z;
c = a+b;
z = x+y;
```

The operators = and + do quite different things in the last two statements: the first statement does *integer* addition and assignment and the second does *floating point* addition and assignment. Operator overloading is simply an extension of this.

C++ recognizes a function name having the form `operator@` as an overloading of the C++ operator symbol `@`. We can overload the operator `+`, for example, by declaring the member function named `operator+`, as we have done in our example class `BigInt`. We can call this function using either the usual notation for calling member functions or by using just the operator:

```
BigInt a,b,c;
c = a.operator+(b);
c = a + b;
```

The last two lines are equivalent.[2]

Of course, if we overload an operator, we don't change its built-in meaning, we only give it an additional meaning when used on instances of our new abstract data type. The expression `2+2` still gives `4`.

Destructors

The last thing we said was that C++ needed to know how to destroy instances of our `BigInt`s once it was finished with them. We can tell the C++ compiler how to do this by defining another special kind of member function called a *destructor*. A destructor function has the same name as its class, prefixed by the character ~. For class `BigInt`, this is the member function `~BigInt()`. Since ~ is the C++ and C complement operator, this naming convention suggests that destructors are complementary to constructors.

We must write the function `~BigInt()` so that it properly cleans-up, or *finalizes* instances of class `BigInt` for which it is called. In our example, this means freeing the dynamic storage that was allocated by the constructor.

If a class has a destructor function, C++ *guarantees* that it will be called to finalize every instance of the class when it is no longer needed. Once again, this relieves users of an abstract data type like `BigInt` from having to remember to do this, and eliminates another source of programming errors.

Summary

We've covered a lot of territory already, so let's review where we've been.

We've seen how using the technique of data abstraction can lead to more reliable, more readable, and more flexible programs, and we've introduced many of the features of C++ that help us practice data abstraction:

- *classes,* the basic language construct for defining new abstract data types;
- *member variables*, which describe the data in an abstract class, and *member functions*, which define the operations on an abstract class;
- *encapsulation*, which lets us restrict access to certain member variables and functions;
- *function argument type checking*, which helps to ensure that functions are called with proper arguments;
- *function name overloading*, which reduces the need for using unusual function names and helps to generalize code;
- *constructors and destructors*, which manage the storage for an abstract data type and guarantee that instances of an abstract data type are initialized and finalized;
- *user-defined implicit type conversion*, to let us blend our abstract data types with others and with the fundamental data types of the language; and,
- *operator overloading*, to let us give additional meaning to most of the existing operators when used with our own abstract data types, making our new data types easier to use.

We've also introduced the idea of breaking up an abstract data type into its specification, which contains the information that the user, or client, needs to know to use the abstract data type, and its implementation, which hides the details of how the abstract data type works so that it may be programmed independently by a member of a programming team and be easily maintained.

The Implementation

We've just taken a detailed look at the specification of our `BigInt` abstract data type. Now it's time to discuss its implementation.

As we said earlier, the implementation of an abstract data type consists of the C++ code that embodies the details of *how* the data abstraction works. For our example it is kept in a separate file named `BigInt.c`.

The implementation requires the information kept in the specification, so the first line in `BigInt.c` is:

```
#include "BigInt.h"
```

Since both the implementation and client programs are compiled with the same specification, the C++ compiler ensures a consistent interface between them.

The `BigInt(const char*)` Constructor

Class `BigInt` has three constructors, one to create an instance of a `BigInt` from a character string of digits (a `char*`), one to create an instance from an integer (an `int`), and one to initialize one `BigInt` from another. We need to be able to create a `BigInt` from a string of digits because this is the only way we can legally write very large integer constants in C++. Creating a `BigInt` from an `int` is provided as a convenience, so we can write small integers in the usual way.

Here is the implementation of the first constructor:

```
BigInt::BigInt(const char* digitString)
{
        int n = strlen(digitString);
        if (n != 0) {
                digits = new char[ndigits=n];
                char* p = digits;
                const char* q = &digitString[n];
                while (n--) *p++ = *--q - '0';
        }
        else {                          // empty string
                digits = new char[ndigits=1];
                digits[0] = 0;
        }
}
```

This constructor initializes the data structure of a `BigInt` as we described previously. We determine the length of the character string argument, allocate enough memory to hold the digits of the number, then scan the character string from right to left, converting each digit character to its binary representation.

If the character string is empty we treat this as a special case and create a `BigInt` initialized to zero.

C programmers will find this code quite recognizable, with a few exceptions that we'll explain in the next few sections.

The Scope Resolution Operator

The notation `BigInt::BigInt` identifies `BigInt` as a member function of class `BigInt`. We mentioned earlier that several C++ classes can have member functions with the same names. When it is necessary to specify exactly *which* class member we're dealing with, we can prefix the member name by the class name and the `::` operator. The `::` operator is known as the *scope resolution operator*, and it may be applied to both member functions and member variables.

Constant Types

C programmers will be familiar with use of the type `char*` for arguments that are character strings, but what is a `const char*`? In C++, the keyword `const` can be used before a type to indicate that the variable being declared is constant, and therefore may not appear to the left of the assignment (=) operator. When used in an argument list as it is above, it prevents the argument from being modified by the function. This protects against another kind of common programming error.

Member Variable References

Throughout the body of the member function, you'll notice that we are able to reference the member variables of the instance for which the function is called without using the . or -> operators, as we did for example in the statement:

```
digits = new char[ndigits=n];
```

Since member functions reference the member variables of their class frequently, this provides a convenient, short notation.

The `new` Operator

We used the C++ `new` operator to allocate the dynamic storage needed to hold the digits of a `BigInt`. In C, we would call the standard C library function `malloc()` to do this. The `new` operator has two advantages, however. First, it returns a pointer of the appropriate data type. Thus, to allocate space for the member variables of a `struct BigInt` in C we would write:

```
(struct BigInt*)malloc(sizeof(struct BigInt))
```

whereas in C++ we can write:

```
new BigInt
```

The second advantage is that if we use `new` to allocate an instance of a class having a constructor function (such as `BigInt`), the constructor is called automatically to initialize the newly allocated instance. The result is more readable, less error-prone code.

Placement of Declarations

C programmers may have noticed that the declaration of `p` seems to be "misplaced":

```
if (n != 0) {
        digits = new char[ndigits=n];      // a statement
        char* p = digits;                  // a declaration!
```

since it appears *after* the first statement in a block. In C++, declarations may be intermixed with statements as long as each variable is declared before its first use. You can frequently improve the readability of a program by placing variable declarations near the place where they are used.

The `BigInt(int)` Constructor

Here's the implementation of the `BigInt(int)` constructor, which creates a `BigInt` from an integer:

```
BigInt::BigInt(int n)
{
        char d[3*sizeof(int)+1];        // buffer for decimal digits
        char* dp = d;                   // pointer to next decimal digit
        ndigits = 0;
        do {                            // convert integer to decimal digits
                *dp++ = n%10;
                n /= 10;
                ndigits++;
        } while (n > 0);
        digits = new char[ndigits];
        register int i;
        for (i=0; i<ndigits; i++) digits[i] = d[i];
}
```

This constructor works by converting the integer argument to decimal digits in the temporary array `d`. We then know how much space to allocate for the `BigInt`, so we allocate the correct amount of dynamic storage using the `new` operator, and copy the decimal digits from the temporary array into it.

The Initialization Constructor

The job of the initialization constructor is to copy the value of its `BigInt` argument into a new instance of `BigInt`:

```
void BigInt::BigInt(const BigInt& n)
{
        int i = n.ndigits;
        digits = new char[ndigits=i];
        char* p = digits;
        char* q = n.digits;
        while (i--) *p++ = *q++;
}
```

This function makes use of a *reference*, an important C++ feature we haven't seen before.

References

The argument type of the member function `BigInt(const BigInt&)` is an example of a C++ *reference*. References address a serious deficiency of C: the lack of a way to pass function arguments by reference.

To understand what this means, suppose we wish to write a function named `inc()` that adds one to its argument. If we wrote this in C as:

```
void inc(x)
int x;
{
        x++;
}
```

and then called `inc()` with the following program:

```
int y = 1;
inc(y);
printf("%d\n",y);
```

we would discover that the program would print a `1`, not a `2`. This is because in C the *value* of `y` is *copied* into the argument `x`, and the statement `x++` increments this copy, leaving the value of `y` unchanged. This treatment of function arguments is known as *call by value.*

To do this correctly in C we must explicitly pass a pointer as the argument to `inc()`:

```
void inc(x)
int* x;
{
        *x++;
}

int y = 1;
inc(&y);
printf("%d\n",y);
```

Notice that we had to change the program in three ways:

- the type of the function argument was changed from an `int` to an `int*`;
- each occurrence of the argument in the body of the function was changed from `x` to `*x`; and,
- each call of the function was changed from `inc(y)` to `inc(&y)`.

The point is that passing a pointer as a function argument requires consistency in every usage of the argument within the function body and, worse yet, in every call of the function made by client programs. This, combined with C's lack of function argument type checking, results in ample opportunity for error.

Using a C++ reference, we can write the function `inc()` as follows:

```
void inc(int& x)
{
        x++;
}

int y = 1;
inc(y);
printf("%d\n",y);
```

This requires changing only the argument type from `int` to `int&`.

In the function `inc()`, we need to pass the argument `x` using a reference because its value is modified by the function. But efficiency is another reason for passing arguments by reference. When the value of an argument requires a lot of storage, as in the case of `BigInt`s, it is less expensive to pass a pointer to the argument even though its value is not to be changed. That's why we declared the argument to `BigInt` as `const BigInt&` — the reference `BigInt&` causes just a pointer to the argument to be passed, but the `const` prevents that pointer from being used to change the argument's value from within the function.

The Addition Operator

Let's take a look at a first draft of the function `operator+`, which implements `BigInt` addition:

```
BigInt BigInt::operator+(const BigInt& n)
{
// Calculate maximum possible number of digits in sum
        int maxDigits = (ndigits>n.ndigits ? ndigits : n.ndigits)+1;
        char* sumPtr = new char[maxDigits];  // allocate storage for sum
        BigInt sum(sumPtr,maxDigits);        // must define this constructor
        int i = maxDigits;
        int carry = 0;
        while (i--) {
                *sumPtr = /*next digit of this*/ + /*next digit of n*/ + carry;
                if (*sumPtr > 9) {
                        carry = 1;
                        *sumPtr -= 10;
                }
                else carry = 0;
                sumPtr++;
        }
        return sum;
}
```

We add two `BigInt`s by using the paper-and-pencil method we all learned in grammar school: we add the digits of each operand from right to left, beginning with the rightmost, and also add a possible carry in from the previous column. If the sum is greater than nine, we subtract ten from the result and produce a carry.

The `BigInt(char*,int)` constructor

We ran into a couple of problems when writing the addition function which we indicated with comments in the code. The first problem is that we need to declare an instance of `BigInt` named `sum` in which to place the result of the addition, which will be left in the array pointed to by `sumPtr`. We must use a constructor to create this instance of `BigInt`, but none of those we have defined thus far are suitable, so we must write another.

This new constructor takes a pointer to an array containing the digits and the number of digits in the array as arguments and creates a `BigInt` from them. We don't want our client programs to use such an unsafe and implementation-dependent function, so we'll declare it in the private part of class `BigInt` where it can only be used by member functions. Thus, we add the declaration:

```
BigInt(char*,int);
```

just before the keyword `public:` in the declaration of class `BigInt` in the file `BigInt.h`, and we add the implementation of this constructor to the file `BigInt.c`:

```
BigInt::BigInt(char* d, int n)
{
        digits = d;
        ndigits = n;
}
```

Class DigitStream

The second problem we encountered is that scanning the digits of the operands in the statement:

```
*sump = /*next digit of this*/ + /*next digit of n*/ + carry;
```

becomes complicated because one of the operands may contain fewer digits than the other, in which case we must pad it to the left with zeros. We would also face this problem when implementing `BigInt` subtraction, multiplication, and division, so it is worthwhile to find a clean solution. Let's use an abstract data type!

Here is the declaration for class `DigitStream` and the implementation of its member functions:

```
class DigitStream {
        char* dp;                       // pointer to current digit
        int nd;                         // number of digits remaining
public:
        DigitStream(const BigInt& n); // constructor
        int operator++();               // return current digit and advance
};

DigitStream::DigitStream(BigInt& n)
{
        dp = n.digits;
        nd = n.ndigits;
}

int DigitStream::operator++()
{
        if (nd == 0) return 0;
        else {
                nd--;
                return *dp++;
        }
}
```

We can now declare an instance of a `DigitStream` for each of the operands and use the ++ operator when we need to read the next digit.

With these two problems solved, the implementation of the `BigInt` addition operator looks like:

```
BigInt BigInt::operator+(const BigInt& n)
{
        int maxDigits = (ndigits>n.ndigits ? ndigits : n.ndigits)+1;
        char* sumPtr = new char[maxDigits];
        BigInt sum(sumPtr,maxDigits);
        DigitStream a(*this);
        DigitStream b(n);
        int i = maxDigits;
        int carry = 0;
        while (i--) {
                *sumPtr = (a++) + (b++) + carry;
                if (*sumPtr > 9) {
                carry = 1;
                *sumPtr -= 10;
                }
                else carry = 0;
                sumPtr++;
        }
        return sum;
}
```

Friend Functions

Our abstract data type `DigitStream` looks quite elegant, but you may be wondering how the constructor `DigitStream(const BigInt&)` is able to access the member variables `digits` and `ndigits` of class `BigInt`. After all, `digits` and `ndigits` are private, and `DigitStream(const BigInt&)` is not a member function of class `BigInt`.

Well, it can't. We need a way to grant access to these variables to just this one function. C++ provides us with a way to do this — we can make this constructor a `friend` of class `BigInt` by adding the declaration:

```
friend DigitStream::DigitStream(const BigInt&);
```

to the declaration of class `BigInt`.

We can also make *all* of the member functions of one class friends of another by declaring the entire class as a `friend`. For example, we can make *all* of the member functions of class `DigitStream` friends of class `BigInt` by placing the declaration:

```
friend DigitStream;
```

in the declaration of class `BigInt`.

The Keyword `this`

Going back to the implementation of the function `operator+()`, you may be wondering where the pointer variable `this` came from in the declaration:

```
DigitStream a(*this);
```

Previously, we described how within the body of a member function we could refer to the members of the instance for which the function was called without using the `.` or -> operators. C++ also gives us the keyword `this` so that we may refer to the entire instance as a unit. The keyword `this` is essentially a pointer to this instance, and in our example may be thought of as a variable of type `BigInt*`. Thus, the declaration `DigitStream a(*this)` creates an instance of `DigitStream` for the left operand of `operator+()`.

The Member Function `BigInt::print()`

The implementation of the member function `print()` is straightforward:

```
void BigInt::print()
{
        int i;
        for (i = ndigits-1; i >= 0; i--) printf("%d",digits[i]);
}
```

It loops through the `digits` array from the most significant through the least significant digits, calling the standard C library function `printf()` to print each digit.

The `BigInt` Destructor

The only thing that the `BigInt` destructor function `~BigInt()` must do is free the dynamic storage allocated by the constructors:

```
BigInt::~BigInt()
{
        delete digits;
}
```

This is done using the C++ `delete` operator, which in this case frees the dynamic storage that is pointed to by `digits`. The `delete` operator does what is usually accomplished in C by calling the standard C library function `free`, but in addition, if we use `delete` to deallocate an instance of a class having a destructor function, the destructor is called automatically to finalize the instance just before its storage is freed. The `delete` operator is thus the inverse of the `new` operator.

Inline Functions

By now you may be thinking that the overhead of calling all of these little member functions must make C++ inefficient. This would be unacceptable for a proper successor to C, which is renowned for its efficiency! So C++ allows us to declare a function to be `inline`, in which case each call of the function is replaced by a copy of the entire function, much like the substitution performed for the `#define` preprocessor command. This entirely eliminates the overhead of calling a function, and makes encapsulation practical.

To make a function such as `~BigInt()` inline, we must move its implementation from the file `BigInt.c` to the file `BigInt.h` and add the keyword `inline` to the function definition:

```
inline BigInt::~BigInt()
{
        delete digits;
}
```

The function definition must be in `BigInt.h` because it will be needed by the compiler whenever a client program uses a `BigInt`.

Small functions make the best candidates for inline compilation. C++ gives us a convenient shorthand for writing `inline` functions: we can include the function body in the function declaration within the `class` declaration. Thus, we can also make `~BigInt() inline` by writing:

```
~BigInt()   { delete digits; }
```

in the declaration of class `BigInt`.

Here is a complete version of `BigInt.h` showing appropriate functions made `inline`:

```
#include <stdio.h>

class BigInt {
        char* digits;                   // pointer to digit array in free store
        int ndigits;                    // number of digits
        BigInt(char* d, int n) {        // constructor function
                digits = d;
                ndigits = n;
        }
        friend DigitStream;
public:
        BigInt(const char*);            // constructor function
        BigInt(int);                    // constructor function
        BigInt(const BigInt&);          // initialization constructor function
        BigInt operator+(const BigInt&); // addition operator function
        void print();                   // printing function
        ~BigInt()    { delete digits; } // destructor function
};
```

```
class DigitStream {
      char* dp;                         // pointer to current digit
      int nd;                           // number of digits remaining
public:
      DigitStream(const BigInt& n) {    // constructor function
            dp = n.digits;
            nd = n.ndigits;
      }
      int operator++() {                // return current digit and advance
            if (nd == 0) return 0;
            else {
                  nd--;
                  return *dp++;
            }
      }
};
```

Summary

This completes our example abstract data type `BigInt`. Let's review the C++ features presented in this section:

- the *scope resolution operator,* which allows us to specify which class we mean when one or more classes have member variables or functions with the same name;
- *constant types,* which we can use to protect variables or function arguments from unintended modification;
- *implicit member variable references* and the keyword `this`, which are used within member functions to access the instance for which the function is called;
- the `new` and `delete` operators, which manage the free storage area and call class constructors/destructors if present;
- *references,* which we can use to conveniently pass pointers to instances instead of the instances themselves as function arguments;
- *friend functions,* which give us a way to grant access to the private member variables and functions of a class to other functions and classes; and,
- *inline functions,* which make data abstraction in C++ efficient and practical.

Other Uses for Abstract Data Types

Our `BigInt` abstract data type is an obvious application for the technique of data abstraction because it is a numeric data type, like `int`, and it is natural to extend the meanings of C++'s arithmetic operators to apply to `BigInts`. As you become more familiar with this technique, you'll discover many opportunities for using abstract data types in your programs. Here are a few examples:

Dynamic Character Strings

We can define a dynamic (i.e., variable length) character string abstract data type that works like the string variables in languages such as BASIC. We can overload the operators `&` and `&=` to concatenate character strings, overload the relational operators `<`, `<=`, `==`, and so on to compare character strings, and overload the array subscript operator `[]` to address the individual characters of a string. The function call operator:

```
    operator() (int position, int length)
```

can be overloaded to perform substring extraction and replacement.

Complex Numbers

C++, like C, doesn't have a built-in complex data type, but it's easy to define one in C++. In fact, one is distributed with the C++ compiler. Class `complex` has two member variables of type `double` that hold the real and imaginary parts of a complex number, and all of the usual arithmetic operators are overloaded to perform complex arithmetic when applied to instances of class `complex`. Many of the functions in the math library, such as `cos()` and `sqrt()`, are overloaded for complex arguments.

Vectors

Vectors are another useful abstract data type. We can define classes for vectors of the fundamental data types, such as `FloatVec`, `DoubleVec`, and `IntVec`, and overload the arithmetic operators to apply element-by-element to vectors. The array subscript operator `[]` can be overloaded to check the range of vector subscripts or to handle vectors with arbitrary subscript bounds. It's also possible to overload the function call operator `()` to subscript multi-dimensional arrays.

Stream I/O

A stream I/O package is distributed with the C++ compiler that defines the class `iostream` (input/output stream) for doing formatted I/O. This class defines an instance named `cin` connected to the standard input file and overloads the operator >> for all the fundamental data types so we can write:

```
float x;
int i;
char* s;
cin >> x >> i >> s;
```

to read a `float`, an `int`, and a character string from the standard input file, for example. The advantage of this over using the C library function `scanf()` is that it is not possible to make the following types of errors:

```
int i;
scanf("%f",&i);     // float format for int
scanf("%d",i);      // int instead of int*
```

Similarly, class `iostream` defines an instance named `cout` connected to the standard output file and an instance named `cerr` connected to the standard error file. It overloads the operator << for all the fundamental data types so we can write:

```
cout << x << i << s;
```

to write a `float`, and `int`, and a character string to the standard output file.

We can also add our own overloadings for the operators >> and << for classes we've written so we can read or write instances of these classes using the same notation.

Object-Oriented Programming in C++

Perhaps the most interesting features of C++ are those that support the style of programming known as *object-oriented programming*. Object-oriented programming is generally useful, but is particularly suited for interactive graphics, simulation, and systems programming applications.

Derived Classes

Suppose we have written a C++ class defining an abstract data type, and we need another abstract data type that is similar to it. Perhaps it requires some additional member variables or functions, or a few of its member functions must do something differently. We'd like to reuse the code we've already written and debugged as much as possible. C++ gives us a simple way to accomplish this: we can declare the new class as a *derived class* of our existing class, called the *base class*. The derived class *inherits* all of the member variables and functions of its base class. We can then differentiate the derived class from its base class by adding member variables, adding member functions, or re-defining member functions inherited from the base class.

A base class may have more than one derived class, and a derived class may, in turn, serve as the base class for other derived classes. Thus, we can define an entire tree-structured arrangement of related classes. This gives us a coherent way to organize classes and to share common code among them.

Virtual Functions

Now suppose we're writing a graphics package, and we've written some classes for various geometric shapes, such as `Line`, `Triangle`, `Rectangle`, and `Circle`. All of these classes implement some of the same member functions, for example `draw()` and `move()`. The relevant `class` declarations for class `Line` and class `Circle` would look like this:

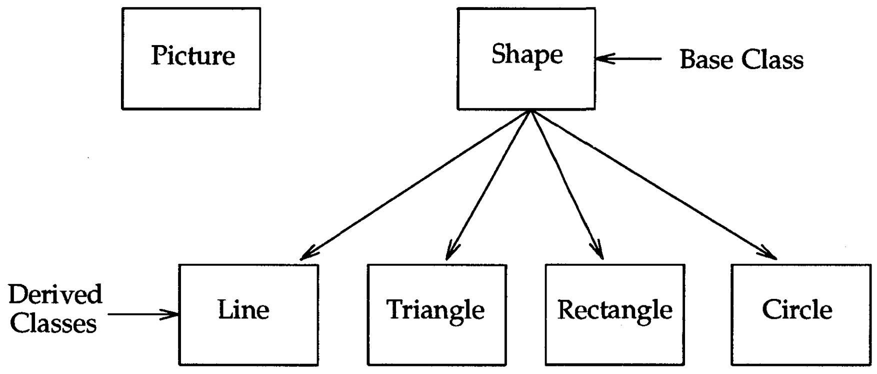
```
class Line {
      int x1,y1,x2,y2;                          // end point coordinates
public:
      Line(int xx1,int yy1,int xx2,int yy2)   // constructor
             { x1=xx1; y1=yy1; x2=xx2; y2=yy2; }
      void draw();                              // draw a line from (x1,y1) to (x2,y2)
      void move(int dx, int dy);                // move line by amount dx,dy
};

class Circle {
      int x,y;                                  // center of circle
      int r;                                    // radius of circle
public:
      Circle(int xx,int yy,int rr)              // constructor
             { x=xx; y=yy; r=rr; }
      void draw();                              // draw circle with center (x,y) and radi
      void move(int dx, int dy);                // move circle by amount dx,dy
};
```

There are a couple of things we'd like to be able to do with these related classes. First, it would be useful to have an abstract data type called `Picture` that would be a collection of `Lines`, `Triangles`, `Rectangles`, and `Circles`. Second, we'd like to be able to `draw()` and `move()` our `Pictures`.

It would be most elegant if class `Picture` were general, and contained no mention of the specific shapes. That way, we could introduce a new shape, say a `Pentagon`, and not have to change class `Picture` in any way.

We can do this by defining a base class `Shape` with derived classes `Line`, `Triangle`, and so on, as shown in Figure 2-6.

Figure 2-6: Organization of Classes for a Graphics Package



Class `Shape` declares functions applicable to any kind of shape such as `draw()` and `move()` as `virtual` functions, and implements these functions to write out an error message if called:

```
class Shape {
public:
      virtual void draw();              // Shape::draw() prints error message
      virtual void move(int dx, int dy); // Shape::move() prints error message
};
```

We change the declarations of classes `Line`, `Triangle`, and so on to be derived from class `Shape` by adding the name of the base class to the declaration of the derived class; for example:

```
class Line : public Shape { ...

class Circle : public Shape { ...
```

and we also add the keyword `virtual` to the declarations of the functions `draw()` and `move()` in the derived classes. We don't have to change the implementation of these functions, however.

Now we can write class `Picture` to deal only with `Shapes`. We can represent a `Picture` by an array containing pointers to its component `Shapes`, and we can implement `Picture::draw()`, for example, simply by calling `Shape::draw()` for each shape in the picture:

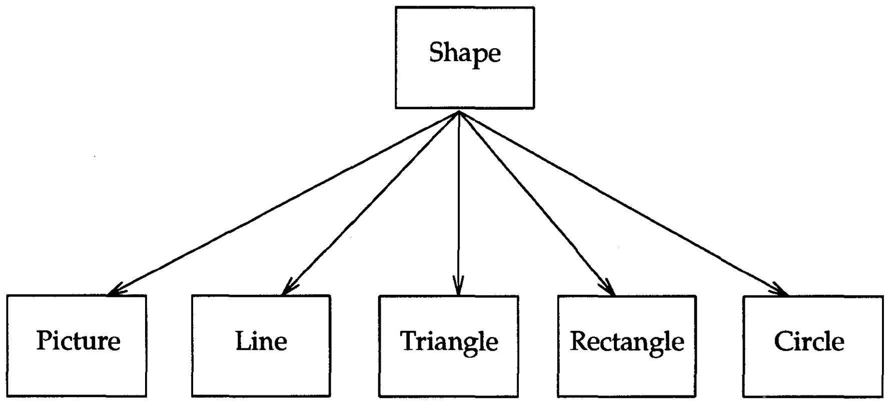
```
const int PICTURE_CAPACITY = 100;       // max number of shapes in picture
class Picture {
        Shape* s[PICTURE_CAPACITY];     // array of pointers to shapes
        int n;                          // current number of shapes in picture
public:
        Picture(){ n = 0; }             // constructor
        void add(const Shape&);         // add shape to picture
        void draw();                    // draw picture
        void move(int dx, int dy);      // move picture
};

void Picture::add(const Shape& t)       // add a shape to a picture
{
        if (n == PICTURE_CAPACITY) {
                cerr << "Picture capacity exceeded\n";
                exit(1);
        }
        s[n++] = &t;                    // add pointer to shape to picture
}

void Picture::draw()                    // draw a picture
{
        int i;
        for (i=0; i<n; i++) s[i]->draw();
}
```

Since `Shape::draw()` is a `virtual` function, C++ takes care of figuring out the specific class of each component `Shape` when the program is executed and calling the appropriate implementation of `draw()` for that class. This is called *dynamic binding*.

If we mistakenly forget to implement `draw()` for a derived class of `Shape`, it will inherit the implementation of `draw()` from class `Shape`. When we try to draw that shape, `Shape::draw()` will be executed, which issues an error message, as you'll recall.

Going a step further, we might want to be able to build a more complicated picture out of a number of simpler pictures. We can do this by thinking of a `Picture` as just another type of `Shape`, and making it another derived class of class `Shape`, leading to the class structure shown in Figure 2-7.

Figure 2-7: Improved Organization of Classes for a Graphics Package



Class Libraries

Taking this technique to its extreme, we can define a class named, say, `Object` and derive *every* class from it, either directly or indirectly. In class `Object` we can declare virtual functions that apply to all classes — functions for copying, printing, storing, reading, and comparing objects, for example. We then can define general data structures comprised of `Objects` and functions that operate on them that will be useful for all classes, just as class `Picture` could work with any derived class of `Shape`.

The author has written a library of about 40 general-purpose classes, modeled after the basic classes of the Smalltalk-80 programming language. The library, known as the Object-Oriented Program Support (OOPS) class library, contains classes such as `String`, Date, (hash tables), `Dictionary` (associative arrays), and `LinkedList`.

Writing C++ programs using a class library such as this is a real delight. The classes are general-purpose, and most programs of any size will have uses for some of them. They are flexible — if a particular class doesn't quite do what is needed it's usually a simple matter to derive a class that does. And the library is extensible. It provides a framework that makes it easy to add your own custom classes and make them function along with existing ones.

As an example, let's see how the OOPS class library can help us with the graphics package we've been discussing. The OOPS library has a class `Point` for representing x-y coordinates. We can use it in graphics classes such as `Line`:

```
class Line : public Shape {
        Point a,b;                      // endpoints of the line
public:
        Line(Point p1, Point p2) { a=p1; b=p2; }    // constructor
        void draw();                    // draw a line from point a to point b
        void move(Point delta);         // move line by delta
};
```

Many of the arithmetic operators are defined by class `Point`, so we can implement `move()`, for example, by writing:

```
void Line::move(Point delta)
{
        a += delta;  b += delta;
}
```

Our crude implementation of class `Picture` allocated an array of fixed size to hold the pointers to its component shapes. We can use the OOPS library class `OrderedCltn` to make this a variable-length array. An `OrderedCltn` is an array of pointers to `Objects`, so we can use it to hold pointers to instances of any class derived from `Object`, just as we used an array of pointers to `Shapes` to hold pointers to `Lines`, `Triangles`, and so on. To make class `Shape` a derived class of `Object`, we modify its declaration:

```
class Shape : public Object { ...
```

Now we can write class `Picture` as:

```
class Picture : public Shape {
        OrderedCltn s;                  // collection of pointers to shapes
public:
        Picture() {}                    // constructor
        virtual void add(const Shape&); // add shape to picture
        virtual void draw();            // draw picture
        virtual void move(Point delta); // move picture
};
```

Class `OrderedCltn` defines member functions such as `add()`, `remove()`, `size()`, `first()`, and `last()` to let us manipulate the pointers in the array. It also overloads the subscript operator `[]` so we can subscript `OrderedCltns` like arrays. Using these we can write the functions `Picture::add()` and `Picture::draw` as follows:

```
void Picture::add(const Shape& t)          // add a shape to a picture
{
        s.add(t);                           // this calls OrderedCltn::add()
}

void Picture::draw()                        // draw a picture
{
        int i;
        for (i=0; i<s.size(); i++)          // s.size() returns # of objects in s
                ((Shape*)s[i])->draw();     // cast address of ith
                                            // to Shape* and call draw()
}
```

Now `Pictures` can have as many shapes in them as we need; class `OrderedCltn` manages the required storage for us.

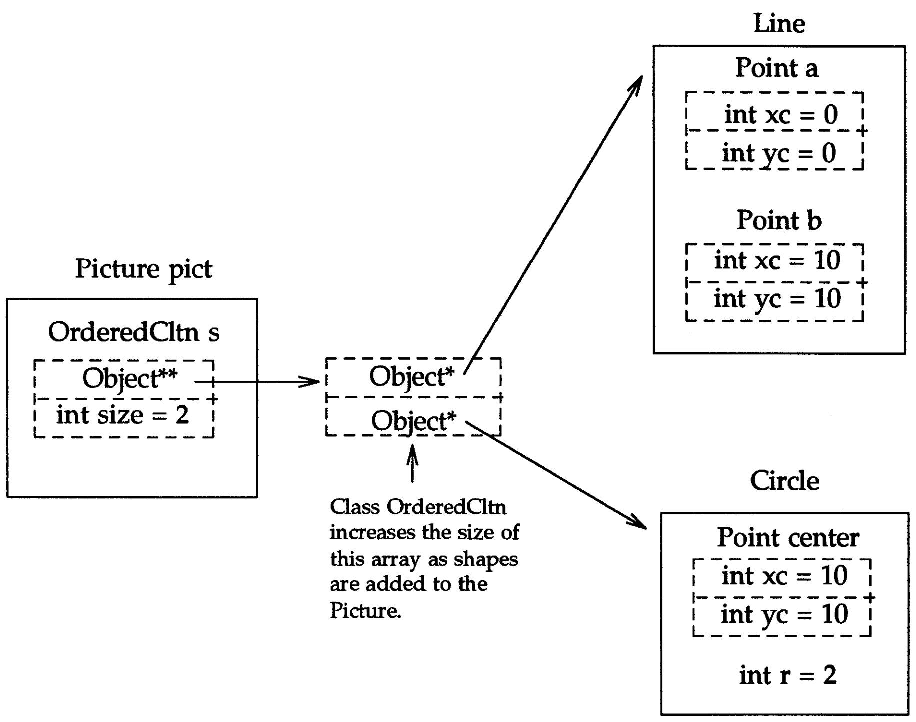
Object I/O

Let's write a program that uses our graphics classes to create a simple picture composed of two shapes — a line and a circle:

```
main()
{
        Picture pict;
        pict.add(*new Line(Point(0,0),Point(10,10)));
        pict.add(*new Circle(Point(10,10),2));
        pict.draw();
}
```

The first statement in the body of `main()` declares an instance of class `Picture` named `pict`, the second statement constructs an instance of `Line` with endpoints at (0,0) and (10,10) and adds it to `pict`, and the third statement constructs an instance of `Circle` with the center at (10,10) and radius 2 and also adds it to `pict`. The result is the data structure shown in Figure 2-8.

Figure 2-8: The data structure of a simple picture. Instances of OOPS library classes are shown as dashed rectangles.



What if we wanted to save this data structure on a disk file so it could be read in later and used by another program? The OOPS class library makes this simple. We create an output stream (an instance of class `fstream`) named, for example, `out`, and write the picture to it with the statements:

```
#include <iostream.h>                 // include header files for
#include <fstream.h>                  // standard C++ stream I/O
// ...
fstream out("picturefile",output);    // create "picturefile"
pict.storeOn(out);
```

The function `storeOn()`, which is implemented in class `Object`, handles the details of finding all of the objects in the picture data structure and writing them to the output stream in a program-independent, machine-independent format. The `storeOn()` function calls the virtual function `storer()` to actually write out member variables. The `storer()` function is declared in class `Object`, and is reimplemented by each derived class to write out its own member variables. This function is already implemented for all of the OOPS library classes, but we must write one for any classes of our own which we've derived from class

Object. That's easy to do. For example, the storer() function for class Picture looks like:

```
void Picture::storer(iostream& strm)
{
        Shape::storer(strm);    // store members of base class, if any
        s.storeOn(strm);        // store member of class Picture
}
```

To read a picture from a file, we create an input stream, in, (an instance of class fstream) connected to the file we wish to read, and read the picture from it with the statements:

```
#include <iostream.h>           // include header files for
#include <fstream.h>            // standard C++ stream I/O
// ...
fstream in("picturefile",input); // open "picturefile" read-only
readFrom(in,"Picture",pict);
```

The second argument tells readFrom() that we're expecting an instance of class Picture to be read, and to complain if the next object on the input stream is of any other class.

The function readFrom() works somewhat like storeOn(), calling a small "reader" function which we must write for each of our classes.

We can use OOPS object I/O to store and read an arbitrarily complex data structure containing instances of both OOPS library classes and our own classes. Since the data structure is converted into a program-independent, machine-independent format, we can send it through a UNIX pipe to another process running on the same machine, or over a network to another process running on a different kind of machine. This capability is particularly useful for spread sheets, forms, documents, drawings, electronic mail, and so on. The OOPS class library also gives us a framework to use when implementing object I/O for our own classes. We don't have to spend time designing a storage format, or worry about such issues as what to do with the pointers in a data structure, for example. We can use the general-purpose mechanism provided by the OOPS class library, and concentrate on our particular application.

The Current Status of C++

The C++ programming language is currently implemented as a *translator,* which accepts C++ source code as input and produces C source code as output. The C++ translator and run-time support library are written in C++, making them easily portable to most UNIX systems.

AT&T first made the C++ translator available to universities and non-profit organizations in December, 1984. Release 1.0 became commercially available as an unsupported product in October, 1985.

The AT&T C++ Language System can run on any UNIX machine capable of running programs up to about 500KB in size, and having a robust C compilation system that can handle variable and external symbol names of arbitrary length. The C compiler must also allow structure assignments and the use of structures as function arguments and return values.

Training and third-party supported ports of the AT&T C++ Translator can be obtained for various UNIX systems, VAX VMS, MS-DOS, and others.

The Future of C++

The definition of the C++ programming language is not yet final. When the ANSI C standard is completed, C++ will undoubtably be revised to eliminate any unnecessary incompatibilities; for example, the ANSI C rules for doing floating point arithmetic will be adopted. Historically, C++ has met the challenge of evolving while remaining compatible with C and earlier versions of C++.

Will the C++ programming language be as successful as its predecessor, or will it become just another of the countless languages that never achieve widespread use? Well, C++ has a lot going for it:

- Since C++ is, with a few minor exceptions, a superset of C, it has no fatal deficiencies. It also possesses those attributes of C that have contributed to C's success: portability, flexibility, and efficiency.
- C++ is less error-prone than C. It thoroughly type-checks programs, as is the trend in modern programming languages, but not at the expense of flexibility or convenience. A programmer may coerce (cast) types when necessary, and define his or her own implicit type conversions for convenience.
- Support for data abstraction and object-oriented programming make C++ a much more powerful and expressive language than C. Yet the language remains one of manageable size, much smaller than PL/1 or ADA, for example.
- C++ programs are compatible with UNIX and with the large number of existing C libraries for graphics, database management, math, and statistics.
- There is a large existing community of C programmers who can begin to use C++ immediately, gradually learning and utilizing its new features.
- The AT&T C++ Language System is commercially available in source form, is inexpensive, and is highly portable. It makes the language accessible on almost all popular operating systems.
- AT&T is developing a portable C++ compiler, which will compile C++ programs more quickly than the combination of the C++ Translator and C compiler now required.
- C++ was designed at the AT&T Bell Laboratories Computer Science Research Center in Murray Hill. They have an impressive track record in producing successful software, such as the UNIX system and C language.

The main obstacle to the widespread adoption of C++ is that to realize its benefits one must master the techniques of data abstraction and/or object-oriented programming — techniques that are unfamiliar to the current generation of programmers. When this educational problem is solved, C++ should succeed C as the language of choice for a wide range of applications.

Footnotes

1. This paper fits the description in the U.S. Copyright Act of a "United States Government work." It was written as a part of the author's official duties as a Government employee. This means it cannot be copyrighted. This paper is freely available to the public for use without a copyright notice, and there are no restrictions on its use, now or subsequently.

   The author's time and the computer facilities required to prepare this paper were provided by the Computer Systems Laboratory, Division of Computer Research and Technology, National Institutes of Health.

2. Binary operators such as `+` are usually not defined as member functions because automatic conversion of types is not done for the left operand. For example, the expression `a + 47` is equivalent to `a.operator+(47)`. C++ recognizes that the function `operator+(const BigInt&)` is defined and that the constructor `BigInt(int)` can be used to convert the `int 47` to a `BigInt` before calling `operator+`. However, the expression `47 + a` is equivalent to `47.operator+(a)`, which is an error because `47` is not an instance of a class and therefore has no member functions that can be applied to it. For this reason, binary operators are usually defined as *friend* functions, which are discussed later.

3 An Overview of C++

An Overview of C++

NOTE

This chapter is taken directly from a paper by Bjarne Stroustrup.

Introduction

C++ is a general purpose programming language designed to make programming more enjoyable for the serious programmer. Except for minor details, C++ is a superset of the C language. C++ was designed to

- be a better C
- support data abstraction
- support object-oriented programming

This paper describes the features added to C to achieve this. In addition to C, the main influences on the design of C++ were Simula67 and Algol68.

C++ has been in use for about four years and has been applied to most branches of systems programming including compiler construction, data base management, graphics, image processing, music synthesis, networking, numerical software, programming environments, robotics, simulation, and switching. It has a highly portable implementation and there are now thousands of installations including AT&T 3B, DEC VAX, Intel 80286, Motorola 68000, and Amdahl machines running UNIX and other operating systems.

What is Good about C?

C is clearly not the cleanest language ever designed nor the easiest to use; so why do so many people use it?

- C is flexible: it is possible to apply C to most every application area, and to use most every programming technique with C. The language has no inherent limitations that preclude particular kinds of programs being written.
- C is efficient: the semantics of C are "low level"; that is, the fundamental concepts of C mirror the fundamental concepts of a traditional computer. Consequently, it is relatively easy for a compiler and/or a programmer to utilize hardware resources for a C program efficiently.
- C is available: given a computer, whether the tiniest micro or the largest super-computer, the chance is that there is an acceptable quality C compiler available and that that C compiler supports an acceptably complete and standard C language and library. There are also libraries and support tools available, so that a programmer rarely needs to design a new system from scratch.
- C is portable: a C program is not automatically portable from one machine (and operating system) to another nor is such a port necessarily easy to do. It is, however, usually possible and the level of difficulty is such that porting even major pieces of software with inherent machine dependences is typically technically and economically feasible.

Compared with these "first order" advantages, the "second order" drawbacks like the curious C declarator syntax and the lack of safety of some language constructs become less important. Designing "a better C" implies compensating for the major problems involved in writing, debugging, and maintaining C programs *without compromising the advantages of* C. C++ preserves all these advantages and compatibility with C at the cost of abandoning claims to perfection and of some compiler and language complexity. However, designing a language "from scratch" does not ensure perfection and the C++ compilers compare favorably in run-time, have better error detection and reporting, and equal the C compilers in code quality.

A Better C

The first aim of C++ is to be "a better C" by providing better support for the styles of programming for which C is most commonly used. This primarily involves providing features that make the most common errors unlikely (since C++ is a superset of C such errors cannot simply be made impossible).

Argument Type Checking and Coercion

The most common error in C programs is a mismatch between the type of a function argument and the type of the argument expected by the called function. For example:

```
double sqrt(a) double a;
{
    /* ... */
}

double sq2 = sqrt(2);
```

Since C does not check the type of the argument `2`, the call `sqrt(2)` will typically cause a run time error or give a wrong result when the square root function tries to use the integer `2` as a double precision floating point number. In C++, this program will cause no problem since `2` will be converted to a floating point number at the point of the call. That is, `sqrt(2)` is equivalent to `sqrt((double)2)`.

Where an argument type does not match the argument type specified in the function declaration and no type conversion is defined the compiler issues an error message. For example, in C++ `sqrt(` causes a compile time error.

Naturally, the C++ syntax also allows the type of arguments to be specified in function declarations:

```
double sqrt(double);
```

and a matching function definition syntax is also introduced:

```
double sqrt(double d)
{
    // ...
}
```

Inline Functions

Most C programs rely on macros to avoid function call overhead for small frequently-called operations. Unfortunately the semantics of macros are very different from the semantics of functions so the use of macros has many pitfalls. For example:

```
#define mul(a,b) a*b
int z = mul(x*3+2,y/4);
```

Here `z` will be wrong since the macro will expand to `x*3+2*y/4`. Furthermore, C macro definitions do not follow the syntactic rules of C declarations, nor do macro names follow the usual C scope rules. C++ circumvents such problems by allowing the programmer to declare `inline` functions:

```
inline int mul(int a, int b) { return a*b; }
```

An inline function has the same semantics as a "normal" function but the compiler can typically inline expand it so that the code-space and run-time efficiency of macros are achieved.

Scoped and Typed Constants

Since C does not have a concept of a symbolic constant macros are used. For example:

```
#define TBLMAX (TBLSIZE-1)
```

Such "constant macros" are neither scoped nor typed and can (if not properly parenthesized) cause problems similar to those of other macros. Furthermore, they must be evaluated each time they are used and their names are "lost" in the macro expansion phase of the compilation and consequently are not known to symbolic debuggers and other tools. In C++ constants of any type can be declared:

```
const int TBLMAX = TBLSIZE-1;
```

Varying Numbers of Arguments

Functions taking varying numbers of arguments and functions accepting arguments of different types are common in C. They are a notable source of both convenience and errors.

C functions where the type of arguments or the number of arguments (but not both) can vary can be handled in a simple and type-secure manner in C++. For example, a function taking one, two, or three arguments of known type can be handled by supplying default argument values which the compiler uses when the programmer leaves out arguments. For example:

```
void print(char*, char* = "-", char* = "-");

print("one", "two", "three");
print("one", "two");  // that is, print("one", "two", "-");
print("one");         // that is, print("one", "-", "-");
```

Some C functions take arguments of varying types to provide a common name for functions performing similar operations on objects of different types. This can be handled in C++ by overloading a function name. That is, the same name can be used for two functions provided the argument types are sufficiently different to enable the compiler to "pick the right one" for each call. For example:

```
void print(int);
void print(char*);

print(1);       // integer print function
print("two");   // string print function
```

The most general examples of C functions with varying arguments cannot be handled in a type-secure manner. Consider the standard output function `printf`, which takes a format string followed by an arbitrary collection of arguments supposedly matching the format string:[1]

```
printf("a string");
printf("x = %d\m",x);
printf("name: %s\m size: %d\n", obj.name, obj.size);
```

However, in C++ one can specify the type of initial arguments and leave the number and type of the remaining arguments unspecified. For example, `printf` and its variants can be declared like this:

```
int printf(const char* ...);
int fprintf(FILE*, const char* ...);
int sprintf(char*, const char* ...);
```

These declarations allow the compiler to catch errors such as

```
printf(stderr,"x = %d\m",x);   // error: printf does not take a FILE*
fprintf("x = %d\m",x);         // error: fprintf needs a FILE*
```

Declarations as Statements

Uninitialized variables are another common source of errors. One cause of this class of errors is the requirement of the C syntax that declarations can occur only at the beginning of a block (before the first statement). In C++, a declaration is considered a kind of statement and can consequently be placed anywhere. It is often convenient to place the declaration where it is first needed so that it can be initialized immediately. For example:

```
void some_function(char* p)
{
    if (p==0) error("p==0 in some_function");
    int length = strlen(p);
    // ...
}
```

Support for Data Abstraction

C++ provides support for data abstraction: the programmer can define types that can be used as conveniently as built-in types and in a similar manner. Arithmetic types such as rational and complex numbers are common examples:

```
class complex {
    double re, im;
public:
    complex(double r, double i) { re=r; im=i; }
    complex(double r) { re=r; im=0; }    // float->complex conversion

    friend complex operator+(complex, complex);
    friend complex operator-(complex, complex);    // binary minus
    friend complex operator-(complex);             // unary minus
    friend complex operator*(complex, complex);
    friend complex operator/(complex, complex);
    // ...
}
```

The declaration of class (that is, user-defined type) `complex` specifies the representation of a complex number and the set of operations on a complex number. The representation is *private;* that is, `re` and `im` are accessible only to the functions defined in the declaration of class `complex`. Such functions can be defined like this:

```
complex operator+(complex a1, complex a2)
{
    return complex(a1.re+a2.re, a1.im+a2.im);
}
```

and used like this:

```
main()
{
    complex a = 2.3;
    complex b = 1/a;
    complex c = a+b+complex(1,2.3);
    // ...
}
```

Functions declared in a class declaration using the keyword `friend` are called *friend functions*. They do not differ from ordinary functions except that they may use private members of classes that name them friends. A function can be declared as a friend of more than one class. Other functions declared in a class declaration are called *member functions*. A member function is in the scope of the class and must be invoked for a specific object of that class.

Initialization and Cleanup

When the representation of a type is hidden some mechanism must be provided for a user to initialize variables of that type. A simple solution is to require a user to call some function to initialize a variable before using it. This is error prone and inelegant. A better solution is to allow the designer of a type to provide a distinguished function to do the initialization. Given such a function, allocation and initialization of a variable becomes a single operation (often called instantiation) instead of two separate operations. Such an initialization function is called a constructor. In cases where construction of objects of a type is non-trivial one often needs a complementary operation to clean up objects after their last use. In C++ such a cleanup function is called a destructor. Consider a vector type:

```
class vector {
    int  sz;            // number of elements
    int* v;             // pointer to integers
public:
    vector(int);        // constructor
    ~vector();          // destructor
    // ...
};
```

The `vector` constructor can be defined to allocate a suitable amount of space like this:

```
vector::vector(int s)
{
    if (s<=0) error("bad vector size");
    sz = s;
    v = new int[s];    // allocate an array of "s" integers
}
```

The cleanup done by the `vector` destructor consists of freeing the storage used to store the vector elements for re-use by the free store manager:

```
vector::~vector()
{
    delete v;           // deallocate the memory pointed to by v
}
```

C++ does not support garbage collection. This is, however, compensated for by enabling a type to maintain its own storage management without requiring intervention from a user. Class `vector` is an example of this.

Free Store Operators

The operators `new` and `delete` were introduced to provide a standard notation for free store allocation and deallocation. A user can provide alternatives to their default implementations by defining functions called `operator new` and `operator delete`. For built-in types the `new` and `delete` operators provide only a notational convenience (compared with the standard C functions `malloc()` and `free()`). For user-defined types such as `vector` the free store operators ensure that constructors and destructors are called properly:

```
vector* fct1(int n)
{
    vector v(n);                // allocate a vector on the stack
                                // the constructor is called
    vector* p = new vector(n);  // allocate a vector on the free store
                                // the constructor is called
    // ...
    return p;
    // the destructor is implicitly called for "v" here
}


void fct2()
{
    vector* pv = fct1(10);
    // ...
    delete pv; // call the destructor and free the store
}
```

References

C provides (only) "call by value" semantics for function argument passing; "call by reference" can be simulated by explicit use of pointers. This is sufficient, and often preferable to using "pass by value" for the built-in types of C. However, it can be inconvenient for larger objects[2] and can get seriously in the way of defining conventional notation for user-defined types in C++. Consequently, the concept of a *reference* is introduced. A reference acts as a name for an object; `T&` means reference to `T`. A reference must be initialized and becomes an alternative name for the object it is initialized with. For example:

```
int a = 1;    // "a" is an integer initialized to "1"
int& r = a;   // "r" is a reference initialized to "a"
```

The reference `r` and the integer `a` can now be used in the same way and with the same meaning. For example:

```
int b = r;    // "b" is initialized to the value of "r", that is, "1"
r = 2;        // the value of "r", that is, the value of "a" becomes "2"
```

References enable variables of types with "large representations" to be manipulated efficiently without explicit use of pointers. Constant references are particularly useful:

```
matrix operator+(const matrix& a, const matrix& b)
{
    // code here cannot modify the value of "a" or "b"
}

matrix a = b+c;
```

In such cases the "call by value" semantics are preserved while achieving the efficiency of "call by reference."

Assignment and Initialization

Controlling construction and destruction of objects is sufficient for many, but not all, types. It can also be necessary to control all copy operations. Consider:

```
vector v1(100);       // make v1 a vector of 100 elements
vector v2 = v1;       // make v2 a copy of v1
v1 = v2;              // assign v1 to v2 (that is, copy the elements)
```

Declaring a function with the name `operator=` in the declaration of class `vector` specifies that vector assignment is to be implemented by that function:

```
class vector {
    int* v;
    int  sz;
public:
    // ...
    void operator=(vector&);  // assignment
};
```

Assignment might be defined like this:

```
void vector::operator=(vector& a) // check size and copy elements
{
    if (sz != a.sz) error("bad vector size for =");
    for (int i = 0; i<sz; i++) v[i] = a.v[i];
}
```

Since the assignment operation relies on the "old value" of the vector assigned to, it cannot be used to implement initialization of one vector with another. What is needed is a constructor that takes a vector argument:

```
class vector {
    // ...
    vector(int);       // create vector
    vector(vector&);  // create vector and copy elements
};
```

```
vector::vector(vector& a)     // initialize a vector from another vector
{
    sz = a.sz;                // same size
    v = new int[sz];          // allocate element array
    for (int i = 0; i<sz; i++) v[i] = a.v[i];    // same values
}
```

A constructor like this (of the form `X(X&)`) is used to handle all initialization. This includes arguments passed "by value" and function return values:

```
vector v2 = v1; // use vector(vector&) constructor to initialize

void f(vector);
f(v2);          // use vector(vector&) constructor to pass a copy of v2

vector g(int sz)
{
    vector v(sz);
    return v;   // use vector(vector&) constructor to return a copy of v
}
```

Operator Overloading

As demonstrated above, standard operators like +, -, *, / can be defined for user-defined types, as can assignment and initialization in its various guises. In general, all the standard operators with the exception of

```
.   ?:
```

can be overloaded. The subscripting operator `[ ]` and the function application operator `()` have proven particularly useful. The C "operator assignment" operators, such as += and *=, have also found many uses.

It is not possible to redefine an operator when applied to built-in data types, to define new operators, or to redefine the precedence of operators.

Coercions

User-defined coercions, like the one from floating point numbers to complex numbers implied by the constructor `complex(double)`, have proven unexpectedly useful in C++. Such coercions can be applied explicitly or the programmer can rely on the compiler adding them implicitly where necessary and unambiguous:

```
    complex a = complex(1);
    complex b = 1;          // implicit: 1 -> complex(1)
    a = b+complex(2);
    a = b+2;                // implicit: 2 -> complex(2)
    a = 2+b;                // implicit: 2 -> complex(2)
```

Coercions were introduced into C++ because mixed mode arithmetic is the norm in languages used for numerical work and because most user-defined types used for "calculation" (for example, matrices, character strings, and machine addresses) have natural mappings to and/or from other types.

Great care is taken (by the compiler) to apply user-defined conversions only where a unique conversion exists. Ambiguities caused by conversions are compile time errors.

It is also possible to define a conversion to a type without modifying the declaration of that type. For example:

```
class point {
    float dist;
    float angle;
public:
    // ...
    operator complex()  // convert point to complex number
    {
        return polar(dist,angle);
    }
    operator double()   // convert point to real number
    {
        if (angle) error("cannot convert point to real: angle!=0");
        return dist;
    }
};
```

These conversions could be used like this:

```
void some_function(point a)
{
    complex z = a;      // z = a.operator complex()
    double d = a;       // d = a.operator double()
    complex z3 = a+3;   // z3 = a.operator complex() + complex(3);
    // ...
}
```

This is particularly useful for defining conversions to built-in types since there is no declaration for a built-in type for the programmer to modify. It is also essential for defining conversions to "standard" user-defined types where a change may have (unintentionally) wide ranging ramifications and where the average programmer has no access to the declaration.

Support for Object-Oriented Programming

C++ provides support for object-oriented programming: the programmer can define class hierarchies and a call of a member function can depend on the actual type of an object (even where the actual type is unknown at compile time). That is, the mechanism that handles member function calls handles the case where it is known at compile time that an object belongs to *some* class in a hierarchy, but exactly *which* class can only be determined at run time. See examples below.

Derived Classes

C++ provides a mechanism for expressing commonality among different types by explicitly defining a class to be part of another. This allows re-use of classes without modification of existing classes and without replication of code. For example, given a class `vector`:

```
class vector {
    // ...
public:
    // ...
    vector(int);
    int& operator[](int); // overload the subscripting operator: []
}
```

one might define a vector for which a user can define the index bounds:

```
class vec : public vector {
    int low, high;
public:
    vec(int, int);
    int& operator[](int);
};
```

Defining `vec` as

```
: public vector
```

means that first of all a `vec` is a `vector`. That is, type `vec` has ("inherits") all the properties of type `vec-tor` in addition to the ones declared specifically for it. Class `vector` is said to be the *base* class for `vec`, and conversely `vec` is said to be *derived* from `vector`.

Class `vec` modifies class `vector` by providing a different constructor, requiring the user to specify the two index bounds rather than the size, and by providing its own access function `operator[]()`. A `vec`'s `operator[]()` is easily expressed in terms of `vector`'s `operator[]()`:

```
int& vec::operator[](int i)
{
    return vector::operator[](i-low);
}
```

The scope resolution operator `::` is used to avoid getting caught in an infinite recursion by calling `vec::operator[]()` from itself. Note that `vec::operator[]()` *had* to use a function like vector::operator[]() to access elements. It could not just use vector's members v and sz directly since they were declared *private* and therefore accessible only to vector's member functions.

The constructor for vec can be written like this:

```
vec::vec(int lb, int hb) : vector(hb-lb+1)
{
    if (hb-lb<0) hb = lb;
    low = lb;
    high = hb;
}
```

The construct :vector(hb-lb+1) is used to specify the argument list needed for the base class constructor vector().

Class vec can be used like this:

```
void some_function(int l, int h)
{
    vec v1(l,h);
    const int sz = h-l+1;
    vector v2(sz);
    // ...
    for (int i=0; i<sz; i++) v2[i] = v1[l+i]; // copy elements explicitly
    v2 = v1; // copy elements by using vector::operator=()
}
```

Virtual Functions

Class derivation (often called subclassing) is a powerful tool in its own right but a facility for run-time type resolution is needed to support object-oriented programming.

Consider defining a type shape for use in a graphics system. The system has to support circles, triangles, squares, and many other shapes. First specify a class that defines the general properties of all shapes:

```
class shape {
    point center;
    color col;
    // ...
public:
    point where() { return center; }
    void move(point to) { center = to; draw(); }
    virtual void draw();
    virtual void rotate(int);
    // ...
};
```

The functions for which the calling interface can be defined, but where the implementation cannot be defined except for a specific shape, have been marked *virtual* (the Simula67 and C++ term for "to be defined later in a class derived from this one"). Given this definition one can write general functions manipulating shapes:

```
void rotate_all(shape* v, int size, int angle)
// rotate all members of vector "v" of size "size" "angle" degrees
{
    for (int i = 0; i < size; i++) v[i].rotate(angle);
}
```

For each shape `v[i]`, the proper `rotate` function for the actual type of the object will be called. That "actual type" is not known at compile time.

To define a particular shape we must say that it is a shape (that is, derive it from class `shape`) and specify its particular properties (including the virtual functions):

```
class circle : public shape {
    int radius;
public:
    void draw() { /* ... */ };
    void rotate(int) {}    // yes, the null function
};
```

In many contexts it is important that the C++ virtual function mechanism is very nearly as efficient as a "normal" function call. The additional run-time overhead is about 4 memory references (dependent on the machine architecture and the compiler) and the memory overhead is one word per object plus one word per virtual function per class.

Visibility Control

The basic scheme for separating the (public) user interface from the (private) implementation details has worked out very well for data abstraction uses of C++. It matches the idea that a type is a black box. It has proven to be less than ideal for object-oriented uses.

The problem is that a class defined to be part of a class hierarchy is not simply a black box. It is often primarily a building block for the design of other classes. In this case the simple binary choice *public/private* can be constraining. A third alternative is needed: a member should be private as far as functions outside the class hierarchy are concerned but accessible to member functions of a derived class in the same way that it is accessible to members of its own class. Such a member is said to be *protected*.

For example, consider a class `node` for some kind of tree:

```
class node {
    // private stuff
protected:
    node* left;
    node* right;
    // more protected stuff
public:
    virtual void print();
    // more public stuff
};
```

The pointers `left` and `right` are inaccessible to the general user but any member function of a class derived from class `node` can manipulate the tree without overhead or inconvenience.

The protection/hiding mechanism applies to names independently of whether a name refers to a function or a data member. This implies that one can have `private` and `protected` function members. Usually it is good policy to keep data `private` and present the `public` and `protected` interfaces as sets of functions. This policy minimizes the effect of changes to a class on its users and consequently maximizes its implementor's freedom to make changes.

Another refinement of the basic inheritance scheme is that it is possible to inherit public members of a base class in such a way that they do not become public members of the derived class. This can be used to provide restricted interfaces to standard classes. For example:

```
class dequeue {
    // ...
    void insert(elem*);
    void append(elem*);
    elem* remove();
};
```

Given a dequeue a `stack` can be defined as a derived class where only the `insert()` and `remove()` operations are defined:

```
class stack : private dequeue {  // note: just ":" not ": public" members
                                 // of dequeue are private members of stack
public:
        dequeue::insert;         // make "insert" a public member of stack
        dequeue::remove;         // make "remove" a public member of stack
};
```

Alternatively, inline functions can be defined to give these operations the conventional names:

```
class stack : private dequeue {
public:
        void push(elem* ee) { dequeue::insert(ee); }
        elem* pop() { return dequeue::remove(); }
};
```

What is Missing?

C++ was designed under severe constraints of compatibility, internal consistency, and efficiency: no feature was included that

- would cause a serious incompatibility with C at the source or linker levels
- would cause run-time or space overheads for a program that did not use it
- would increase run-time or space requirements for a C program
- would significantly increase the compile time compared with C
- could only be implemented by making requirements of the programming environment (linker, loader, etc.) that could not be simply and efficiently implemented in a traditional C programming environment

Features that might have been provided but weren't because of these criteria include garbage collection, parameterized classes, exceptions, support for concurrency, and integration of the language with a programming environment. Not all of these possible extensions would actually be appropriate for C++ and unless great constraint is exercised when selecting and designing features for a language a large, unwieldy, and inefficient mess will result. The severe constraints on the design of C++ have probably been beneficial and will continue to guide the evolution of C++.

Conclusions

C++ has succeeded in providing greatly improved support for traditional C-style programming without added overhead. In addition, C++ provides sufficient language support for data abstraction and object-oriented programming in demanding (both in terms of machine utilization and application complexity) real-life applications. C++ continues to evolve to meet demands of new application areas. There still appears to be ample scope for improvement even given the (self imposed) Draconian criteria for compatibility, consistency, and efficiency. However, currently the most active areas of development are not the language itself but libraries and support tools in the programming environment.

Footnotes

1. A C++ I/O system that avoids the type insecurity of the `printf` approach is described in *The C++ Programming Language.*
2. As indicated by an inconsistency in the C semantics, arrays are always passed by reference.

4 Object-Oriented Programming

What is "Object-Oriented Programming"? (1991 revised version)

NOTE

This chapter is taken directly from a paper by Bjarne Stroustrup.

Abstract

"Object-Oriented Programming" and "Data Abstraction" have become very common terms. Unfortunately, few people agree on what they mean. I will offer informal definitions that appear to make sense in the context of languages like Ada, C++, Modula-2, Simula, and Smalltalk. The general idea is to equate "support for data abstraction" with the ability to define and use new types and equate "support for object-oriented programming" with the ability to express type hierarchies. Features necessary to support these programming styles in a general purpose programming language will be discussed. The presentation centers around C++ but is not limited to facilities provided by that language.

Introduction

Not all programming languages can be "object-oriented". Yet claims have been made to the effect that APL, Ada, Clu, C++, CLOS, and Smalltalk are object-oriented programming languages. I have heard discussions of object-oriented design in C, Pascal, Modula-2, and CHILL. As predicted in the original version of this paper, proponents of object-oriented Fortran and Cobol programming are now appearing. "Object-oriented" has in many circles become a high-tech synonym for "good", and when you examine discussions in the trade press, you can find arguments that appear to boil down to syllogisms like:

```
        Ada is good
  Object-oriented is good
----------------------------------
   Ada is object-oriented
```

We simply *must* be more careful with our concepts and logic.

This paper presents one view of what "object-oriented" ought to mean in the context of a general purpose programming language. It:

- Distinguishes "object-oriented programming" and 'data abstraction" from each other and from other styles of programming, and presents the mechanisms that are essential for supporting the various styles of programming.
- Presents features needed to make data abstraction effective.

- Discusses facilities needed to support object-oriented programming.
- Presents some limits imposed on data abstraction and object-oriented programming by traditional hardware architectures and operating systems.

Examples will be presented in C++. The reason for this is partly to introduce C++ and partly because C++ is one of the few languages that supports both data abstraction and object-oriented programming in addition to traditional programming techniques. Issues of concurrency and of hardware support for specific higher-level language constructs are ignored in this paper.

Programming Paradigms

Object-oriented programming is a technique for programming – a paradigm for writing "good" programs for a set of problems. If the term "object-oriented programming language" means anything it must mean a programming language that provides mechanisms that support the object-oriented style of programming well.

There is an important distinction here. A language is said to *support* a style of programming if it provides facilities that makes it convenient (reasonably easy, safe, and efficient) to use that style. A language does not support a technique if it takes exceptional effort or skill to write such programs; it merely *enables* the technique to be used. For example, you can write structured programs in Fortran, write type-secure programs in C, and use data abstraction in Modula-2, but it is unnecessarily hard to do because these languages do not support those techniques.

Support for a paradigm comes not only in the obvious form of language facilities that allow direct use of the paradigm, but also in the more subtle form of compile-time and/or run-time checks against unintentional deviation from the paradigm. Type checking is the most obvious example of this; ambiguity detection and run-time checks can be used to extend linguistic support for paradigms. Extra-linguistic facilities such as standard libraries and programming environments can also provide significant support for paradigms.

A language is not necessarily better than another because it possesses a feature the other does not. There are many example to the contrary. The important issue is not so much what features a language possesses but that the features it does possess are sufficient to support the desired programming styles in the desired application areas:

[1] All features must be cleanly and elegantly integrated into the language.

[2] It must be possible to use features in combination to achieve solutions that would otherwise have required extra separate features.

[3] There should be as few spurious and "special purpose" features as possible.

[4] A feature should be such that its implementation does not impose significant overheads on programs that do not require it.

[5] A user need only know about the subset of the language explicitly used to write a program.

The last two principles can be summarized as "what you don't know won't hurt you." If there are any doubts about the usefulness of a feature it is better left out. It is *much* easier to add a feature to a language than to remove or modify one that has found its way into the compilers or the literature.

I will now present some programming styles and the key language mechanisms necessary for supporting them. The presentation of language features is not intended to be exhaustive.

Procedural Programming

The original (and probably still the most commonly used) programming paradigm is:

Decide which procedures you want;
use the best algorithms you can find.

The focus is on the design of the processing, the algorithm needed to perform the desired computation. Languages support this paradigm by facilities for passing arguments to functions and returning values from functions. The literature related to this way of thinking is filled with discussion of ways of passing arguments, ways of distinguishing different kinds of arguments, different kinds of functions (procedures, routines, macros, ...), etc. Fortran is the original procedural language; Algol60, Algol68, C and Pascal are later inventions in the same tradition.

A typical example of "good style" is a square root function. Given an argument, it produces a result. To do this, it performs a well understood mathematical computation:

```
double sqrt(double arg)
{
    // the code for calculating a square root
}

void some_function()
{
    double root2 = sqrt(2);
    // ...
}
```

From a program organization point of view, functions are used to create order in a maze of algorithms.

Data Hiding

Over the years, the emphasis in the design of programs has shifted away from the design of procedures towards the organization of data. Among other things, this reflects an increase in program size. A set of related procedures with the data they manipulate is often called a *module*. The programming paradigm becomes:

Decide which modules you want;
partition the program so that data is hidden in modules.

This paradigm is also known as the "data hiding principle". Where there is no grouping of procedures with related data the procedural programming style suffices. In particular, the techniques for designing "good procedures" are now applied for each procedure in a module. The most common example is a definition of a stack module. The main problems that have to be solved are:

[1] Provide a user interface for the stack (for example, functions `push()` and `pop()`).

[2] Ensure that the representation of the stack (for example, a vector of elements) can only be accessed through this user interface.

[3] Ensure that the stack is initialized before its first use.

Here is a plausible external interface for a stack module:

```
// declaration of the interface of module stack of characters
char pop();
void push(char);
const stack_size = 100;
```

Assuming that this interface is found in a file called `stack.h`, the "internals" can be defined like this:

```
#include "stack.h"
static char v[stack_size];      // ''static'' means local to this file/module
static char* p = v;             // the stack is initially empty

char pop()
{
    // check for underflow and pop
}

void push(char c)
{
    // check for overflow and push
}
```

It would be quite feasible to change the representation of this stack to a linked list. A user does not have access to the representation anyway (since `v` and `p` were declared `static`, that is, local to the file/module in which they were declared). Such a stack can be used like this:

```
#include "stack.h"

void some_function()
{
    push('c');
    char c = pop();
    if (c != 'c') error("impossible");
}
```

Pascal (as originally defined) doesn't provide any satisfactory facilities for such grouping: the only mechanism for hiding a name from "the rest of the program" is to make it local to a procedure. This leads to strange procedure nestings and over-reliance on global data.

C fares somewhat better. As shown in the example above, you can define a "module" by grouping related function and data definitions together in a single source file. The programmer can then control which names are seen by the rest of the program (a name can be seen by the rest of the program *unless* it has been declared `static`). Consequently, in C you can achieve a degree of modularity. However, there is no generally accepted paradigm for using this facility and the technique of relying on `static` declarations is rather low level.

One of Pascal's successors, Modula-2, goes a bit further. It formalizes the concept of a module, making it a fundamental language construct with well defined module declarations, explicit control of the scopes of names (import/export), a module initialization mechanism, and a set of generally known and accepted styles of usage.

The differences between C and Modula-2 in this area can be summarized by saying that C only *enables* the decomposition of a program into modules, while Modula-2 *supports* that technique.

Data Abstraction

Programming with modules leads to the centralization of all data of a type under the control of a type manager module. If one wanted two stacks, one would define a stack manager module with an interface like this:

```
class stack_id;  // stack_id is a type
                 // no details about stacks or stack_ids are known here

stack_id create_stack(int size); // make a stack and return its identifier
destroy_stack(stack_id);         // call when stack is no longer needed

void push(stack_id, char);
char pop(stack_id);
```

This is certainly a great improvement over the traditional unstructured mess, but "types" implemented this way are clearly very different from the built-in types in a language. Each type manager module must define a separate mechanism for creating "variables" of its type, there is no established norm for assigning object identifiers, a "variable" of such a type has no name known to the compiler or programming environment, nor do such "variables" obey the usual scope rules or argument passing rules.

A type created through a module mechanism is in most important aspects different from a built-in type and enjoys support inferior to the support provided for built-in types. For example:

```
void f()
{
    stack_id s1;
    stack_id s2;

    s1 = create_stack(200);
    // Oops: forgot to create s2

    push(s1,'a');
    char c1 = pop(s1);
    if (c1 != 'a') error("impossible");

    push(s2,'b');
    char c2 = pop(s2);
    if (c2 != 'b') error("impossible");

    destroy_stack(s2);
    // Oops: forgot to destroy s1
}
```

In other words, the module concept that supports the data hiding paradigm enables this style of programming, but does not support it.

Languages such as Ada, Clu, and C++ attack this problem by allowing a user to define types that behave in (nearly) the same way as built-in types. Such a type is often called an *abstract data type*. I prefer the term "user-defined type." A way of defining types that are somewhat more abstract is demonstrated in the "Multiple Implementations" section below.[1] What are referred to as types in this paper would, given such a specification, be concrete specifications of such truly abstract entities. The programming paradigm becomes:

Decide which types you want;
provide a full set of operations for each type.

Where there is no need for more that one object of a type the data hiding programming style using modules suffices. Arithmetic types such as rational and complex numbers are common examples of user-defined types:

```
class complex {
    double re, im;
public:
    complex(double r, double i) { re=r; im=i; }
    complex(double r) { re=r; im=0; }    // float->complex conversion

    friend complex operator+(complex, complex);
    friend complex operator-(complex, complex);    // binary minus
    friend complex operator-(complex);             // unary minus
    friend complex operator*(complex, complex);
    friend complex operator/(complex, complex);
    // ...
};
```

The declaration of class (that is, user-defined type) `complex` specifies the representation of a complex number and the set of operations on a complex number. The representation is *private;* that is, `re` and `im` are accessible only to the functions specified in the declaration of class `complex`. Such functions can be defined like this:

```
complex operator+(complex a1, complex a2)
{
    return complex(a1.re+a2.re,a1.im+a2.im);
}
```

and used like this:

```
complex a = 2.3;
complex b = 1/a;
complex c = a+b*complex(1,2.3);
// ...
c = -(a/b)+2;
```

Most, but not all, modules are better expressed as user-defined types. For concepts where the "module representation" is desirable even when a proper facility for defining types is available, the programmer can declare a type and only a single object of that type. Alternatively, a language might provide a module concept in addition to and distinct from the class concept.

Problems with Data Abstraction

An abstract data type defines a sort of black box. Once it has been defined, it does not really interact with the rest of the program. There is no way of adapting it to new uses except by modifying its definition. This can lead to severe inflexibility. Consider defining a type `shape` for use in a graphics system. Assume for the moment that the system has to support circles, triangles, and squares. Assume also that you have some classes:

```
class point{ /* ... */ };
class color{ /* ... */ };
```

You might define a shape like this:

```
enum kind { circle, triangle, square };

class shape {
    point center;
    color col;
    kind k;
    // representation of shape
public:
    point where()       { return center; }
    void move(point to) { center = to; draw(); }
    void draw();
    void rotate(int);
    // more operations
};
```

The "type field" `k` is necessary to allow operations such as `draw()` and `rotate()` to determine what kind of shape they are dealing with (in a Pascal-like language, one might use a variant record with tag `k`). The function `draw()` might be defined like this:

```
void shape::draw()
{
    switch (k) {
    case circle:
        // draw a circle
        break;
    case triangle:
        // draw a triangle
        break;
    case square:
        // draw a square
    }
}
```

This is a mess. Functions such as `draw()` must "know about" all the kinds of shapes there are. Therefore the code for any such function grows each time a new shape is added to the system. If you define a new shape, every operation on a shape must be examined and (possibly) modified. You are not able to add a new shape to a system unless you have access to the source code for every operation. Since adding a new shape involves "touching" the code of every important operation on shapes, it requires great skill and potentially introduces bugs into the code handling other (older) shapes. The choice of representation of particular shapes can get severely cramped by the requirement that (at least some of) their representation must fit into the typically fixed sized framework presented by the definition of the general type `shape`.

Object-Oriented Programming

The problem is that there is no distinction between the general properties of any shape (a shape has a color, it can be drawn, etc.) and the properties of a specific shape (a circle is a shape that has a radius, is drawn by a circle-drawing function, etc.). Expressing this distinction and taking advantage of it defines object-oriented programming. A language with constructs that allows this distinction to be expressed and used supports object-oriented programming. Other languages don't.

The Simula inheritance mechanism provides a solution. First, specify a class that defines the general properties of all shapes:

```
class shape {
    point center;
    color col;
    // ...
public:
    point where() { return center; }
    void move(point to) { center = to; draw(); }
    virtual void draw();
    virtual void rotate(int);
    // ...
};
```

The functions for which the calling interface can be defined, but where the implementation cannot be defined except for a specific shape, have been marked "virtual" (the Simula and C++ term for "may be redefined later in a class derived from this one"). Given this definition, we can write general functions manipulating shapes:

```
void rotate_all(shape* v, int size, int angle)
// rotate all members of vector "v" of size "size" "angle" degrees
{
    for (int i = 0; i < size; i++) v[i].rotate(angle);
}
```

To define a particular shape, we must say that it is a shape and specify its particular properties (including the virtual functions):

```
class circle : public shape {
    int radius;
public:
    void draw() { /* ... */ };
    void rotate(int) {}     // yes, the null function
};
```

In C++, class `circle` is said to be *derived* from class `shape`, and class `shape` is said to be a *base* of class `circle`. An alternative terminology calls `circle` and `shape` subclass and superclass, respectively.

The programming paradigm is:

> *Decide which classes you want;*
> *provide a full set of operations for each class;*
> *make commonality explicit by using inheritance.*

Where there is no such commonality data abstraction suffices. The amount of commonality between types that can be exploited by using inheritance and virtual functions is the litmus test of the applicability of object-oriented programming to an application area. In some areas, such as interactive graphics, there is clearly enormous scope for object-oriented programming. For other areas, such as classical arithmetic types and computations based on them, there appears to be hardly any scope for more than data abstraction and the facilities needed for the support of object-oriented programming seem unnecessary.[2]

Finding commonality among types in a system is not a trivial process. The amount of commonality to be exploited is affected by the way the system is designed. When designing a system, commonality must be actively sought, both by designing classes specifically as building blocks for other types, and by examining classes to see if they exhibit similarities that can be exploited in a common base class.

Having examined the minimum support needed for procedural programming, data hiding, data abstraction, and object-oriented programming we will go into some detail describing features that – while not essential – can make data abstraction and object-oriented more effective.

Support for Data Abstraction

The basic support for programming with data abstraction consists of facilities for defining a set of operations (functions and operators) for a type and for restricting the access to objects of the type to that set of operations. Once that is done, however, the programmer soon finds that language refinements are needed for convenient definition and use of the new types. Operator overloading is a good example of this.

Initialization and Cleanup

When the representation of a type is hidden some mechanism must be provided for a user to initialize variables of that type. A simple solution is to require a user to call some function to initialize a variable before using it. For example:

```
class vector {
    int  sz;
    int* v;
public:
    void init(int size);    // call init to initialize sz and v
                            // before the first use of a vector
    // ...
};
```

```
vector v;
// don't use v here
v.init(10);
// use v here
```

This is error prone and inelegant. A better solution is to allow the designer of a type to provide a distinguished function to do the initialization. Given such a function, allocation and initialization of a variable becomes a single operation (often called instantiation or construction) instead of two separate operations. Such an initialization function is often called a constructor. In cases where construction of objects of a type is non-trivial, one often needs a complementary operation to clean up objects after their last use. In C++, such a cleanup function is called a destructor. Consider a vector type:

```
class vector {
    int  sz;                      // number of elements
    int* v;                       // pointer to integers
public:
    vector(int);                  // constructor
    ~vector();                    // destructor
    int& operator[](int index);   // subscript operator
};
```

The vector constructor can be defined to allocate space like this:

```
vector::vector(int s)
{
    if (s<=0) error("bad vector size");
    sz = s;
    v = new int[s];   // allocate an array of "s" integers
}
```

The vector destructor frees the storage used:

```
vector::~vector()
{
    delete v;         // deallocate the memory pointed to by v
}
```

C++ does not support garbage collection. This is compensated for, however, by enabling a type to maintain its own storage management without requiring intervention by a user. This is a common use for the constructor/destructor mechanism, but many uses of this mechanism are unrelated to storage management.

Assignment and Initialization

Controlling construction and destruction of objects is sufficient for many types, but not for all. It can also be necessary to control all copy operations. Consider class vector:

```
vector v1(100);
vector v2 = v1;  // make a new vector v2 initialized to v1
v1 = v2;         // assign v2 to v1
```

It must be possible to define the meaning of the initialization of v2 and the assignment to v1. Alternatively it should be possible to prohibit such copy operations; preferably both alternatives should be available. For example:

```
class vector {
    int* v;
    int  sz;
public:
    // ...
    void operator=(const vector&);  // assignment
    vector(const vector&);          // initialization
};
```

specifies that user-defined operations should be used to interpret vector assignment and initialization. Assignment might be defined like this:

```
vector::operator=(const vector& a) // check size and copy elements
{
    if (sz != a.sz) error("bad vector size for =");
    for (int i = 0; i<sz; i++) v[i] = a.v[i];
}
```

Since the assignment operation relies on the "old value" of the vector being assigned to, the initialization operation *must* be different. For example:

```
vector::vector(const vector& a)    // initialize a vector from another vector
{
    sz = a.sz;               // same size
    v = new int[sz];         // allocate element array
    for (int i = 0; i<sz; i++) v[i] = a.v[i];    // copy elements
}
```

In C++, a copy constructor, for example X(const X&) defines all initialization of objects of type X with another object of type X. In addition to explicit initialization copy constructors are used to handle arguments passed "by value" and function return values.

In C++ assignment of an object of class X can be prohibited by declaring assignment private:

```
class X {
    void operator=(const X&);    // only members of X can
    X(const X&);                 // copy an X
    // ...
public:
    // ...
};
```

Ada does not support constructors, destructors, overloading of assignment, or user-defined control of argument passing and function return. This severely limits the class of types that can be defined and forces the programmer back to "data hiding techniques"; that is, the user must design and use type manager modules rather than proper types.

Parameterized Types

Why would you want to define a vector of integers anyway? A user typically needs a vector of elements of some type unknown to the writer of the `vector` type. Consequently the vector type ought to be expressed in such a way that it takes the element type as an argument:

```
template<class T> class vector {     // vector of elements of type T
    T* v;
    int sz;
public:
    vector(int s)
    {
        if (s <= 0) error("bad vector size");
        v = new T[sz = s];     // allocate an array of "s" "T"s
    }
    T& operator[](int i);
    int size() { return sz; }
    // ...
};
```

A `template` specifies a family of types generated by specifying the the template argument(s).

Vectors of specific types can now be defined and used:

```
vector<int> v1(100);      // v1 is a vector of 100 integers
vector<complex> v2(200);  // v2 is a vector of 200 complex numbers

v2[i] = complex(v1[x],v1[y]);
```

Ada, Clu, ML, and C++ support parameterized types.[3] There need not be any run-time overheads compared with a class where all types involved are specified directly.

A problem with parameterized types is that each instantiation creates an independent type. For example, the type `vector<char>` is unrelated to the type `vector<complex>`. Ideally one would like to be able to express and utilize the commonality of types generated from the same parameterized type. For example, both `vector<char>` and `vector<complex>` have a `size()` function that is independent of the parameter type. It is possible, but not trivial, to deduce this from the definition of class `vector` and then allow `size()` to be applied to any `vector`. An interpreted or dynamically compiled language (such as Smalltalk) or a language supporting both parameterized types and inheritance (such as C++) has an advantage here.

Exception Handling

As programs grow, and especially when libraries are used extensively, standards for handling errors (or more generally: "exceptional circumstances") become important. Ada, Algol68, Clu, and C++ each support a standard way of handling exceptions.[4]

Consider again the `vector` example:

```
class vector {
        // ...
        class range { }; // type to be used for exceptions
};

int& vector::operator[](int i)
{
    if (i<0 || sz<=i) throw range();
    return v[i];
}
```

Instead of calling an error function, `vector::operator[]()` can invoke the exception handling code, "throw the range exception." This will cause the call stack to be unraveled until an exception handler for `vector::range` is found; this handler will than be executed.

An exception handler may be defined for a specific block:

```
void f(int i) {
    try {                  // exceptions in this try block are handled by the
                             // exception handler defined below
         vector v(i);
         // ...
        v[i] = 7;        //  causes vector::range exception
        // ...
        int i = g();     // might cause a vector::range exception
    }
    catch (vector::range) {
           error("f(): vector range error");
           return;
    }
}
```

There are many ways of defining exceptions and the behavior of exception handlers. The facility sketched here resembles the ones found in Clu and ML.

A poor implementation of exception handling can be a serious drain on run-time efficiency and the portability of language implementations. The C++ exception handling can be implemented so that code is not executed unless an exception is thrown or portably across C implementations by (implicitly) using the C standard library functions `setjmp()` and `longjmp()`.

Type conversions

User-defined type conversions, such as the one from floating point numbers to complex numbers implied by the constructor `complex(double)`, have proven unexpectedly useful in C++. Such conversions can be applied explicitly or the programmer can rely on the compiler to add them implicitly where necessary and unambiguous:

```
complex a = complex(1);
complex b = 1;          // implicit: 1 -> complex(1)
a = b+complex(2);
a = b+2;                // implicit: 2 -> complex(2)
```

User-defined type conversions were introduced into C++ because mixed mode arithmetic is the norm in languages for numerical work and because most user-defined types used for "calculation" (for example, matrices, character strings, and machine addresses) have natural mappings to and/or from other types.

One use of coercions has proven especially useful from a program organization point of view:

```
complex a = 2;
complex b = a+2;  // interpreted as operator+(a,complex(2))
b = 2+a;          // interpreted as operator+(complex(2),a)
```

Only one function is needed to interpret "+" operations and the two operands are handled identically by the type system. Furthermore, class `complex` is written without any need to modify the concept of integers to enable the smooth and natural integration of the two concepts. This is in contrast to a "pure object-oriented system" where the operations would be interpreted like this:

```
a+2;    // a.operator+(2)
2+a;    // 2.operator+(a)
```

making it necessary to modify class `integer` to make `2+a` legal. Modifying existing code should be avoided as far as possible when adding new facilities to a system. Typically, object-oriented programming offers superior facilities for adding to a system without modifying existing code. In this case, however, data abstraction facilities provide a better solution.

Iterators

It has been claimed that a language supporting data abstraction must provide a way of defining control structures. In particular, a mechanism that allows a user to define a loop over the elements of some type containing elements is often needed. This must be achieved without forcing a user to depend on details of the implementation of the user-defined type. Given a sufficiently powerful mechanism for defining new types and the ability to overload operators, this can be handled without a separate mechanism for defining control structures.

For a vector, defining an iterator is not necessary since an ordering is available to a user through the indices. I'll define one anyway to demonstrate the technique. There are several possible styles of iterators. My favorite relies on overloading the function application operator `()`:[5]

```
class vector_iterator {
    vector& v;
    int i;
public:
    vector_iterator(vector& r) { i = 0; v = r; }
    int operator()() { return i<v.size() ? v.elem(i++) : 0; }
};
```

A `vector_iterator` can now be declared and used for a `vector` like this:

```
void f(vector& v)
{
      vector_iterator next(v);
      int i;
      while (i=next()) print(i);  // maybe too 'cute'
}
```

More than one iterator can be active for a single object at one time, and a type may have several different iterator types defined for it so that different kinds of iteration may be performed. An iterator is a rather simple control structure. More general mechanisms can also be defined. For example, the C++ standard library provides a co-routine clas.s

For many "container" types, such as `vector`, one can avoid introducing a separate iterator type by defining an iteration mechanism as part of the type itself. A `vector` might be defined to have a "current element":

```
class vector {
    int* v;
    int  sz;
    int current;
public:
    // ...
    int next() { return (current < sz) ? v[current++] : 0; }
    int prev() { return (0 <= --current) ? v[current] : 0; }
};
```

Then the iteration can be performed like this:

```
vector v(sz);
int i;
while (i=v.next()) print(i);
```

This solution is not as general as the iterator solution, but avoids overhead in the important special case where only one kind of iteration is needed and where only one iteration at a time is needed for a vector. If necessary, a more general solution can be applied in addition to this simple one. Note that the "simple" solution requires more foresight from the designer of the container class than the iterator solution does. The iterator-type technique can also be used to define iterators that can be bound to several different container types thus providing a mechanism for iterating over different container types with a single iterator type.

Multiple Implementations

The basic mechanism for supporting object-oriented programming, derived classes, and virtual functions can be used to support data abstraction by allowing several different implementations for a given type. Consider again the stack example:

```
template<class T>
        class stack {
        public:
                virtual void push(T) = 0; // pure virtual function
                virtual T pop() = 0;      // pure virtual function
        };
```

The =0 notation specifies that no definition is required for the virtual function and that the class is abstract, that is, the class can only be used as a base class. This allows stacks to be used, but not created:

```
stack<cat> s; // error: stack is abstract

void some_function(stack<cat>& s, cat kitty) // ok
{
        s.push(kitty);
        cat c2 = s.pop();
        // ...
}
```

Since no representation is specified in the stack interface, its users are totally insulated from implementation details.

We can now provide several distinct implementations of stacks. For example, we can provide a stack implemented with an array:

```
template<class T>
      class astack : public stack<T> {
            // actual representation of a stack object
            // in this case an array
            // ...
      public:
            astack(int size);
            ~astack();

            void push(T);
            T pop();
      };
```

and elsewhere a stack implemented using a linked list:

```
template<class T>
      class lstack : public stack<T> {
            // ...
      };
```

We can now create and use stacks:

```
void g()
{
      lstack<cat> s1(100);
      astack<cat> s2(100);

      cat ginger;
      cat snowball;

      some_function(s1,ginger);
      some_function(s2,snowball);
}
```

Only the creator of `stacks`, `g()`, needs to worry about different kinds of `stacks`, the user `some_function()` is totally insulated from such details. The price of this flexibility is that each operation on such a type must be a virtual function.

Implementation Issues

The support needed for data abstraction is primarily provided in the form of language features implemented by a compiler. However, parameterized types are best implemented with support from a linker with some knowledge of the language semantics, and exception handling requires support from the run-time environment. Both can be implemented to meet the strictest criteria for both compile time speed and efficiency without compromising generality or programmer convenience.

As the power to define types increases, programs to a larger degree depend on types from libraries (and not just those described in the language manual). This naturally puts greater demands on facilities to express what is inserted into or retrieved from a library, facilities for finding out what a library contains, facilities for determining what parts of a library are actually used by a program, etc.

For a compiled language, facilities for calculating the minimal compilation necessary after a change become important. It is essential that the linker/loader – with suitable help from the compiler – is capable of bringing a program into memory for execution without also bringing in large amounts of related, but unused, code. In particular, a library/linker/loader system that brings the code for every operation on a type into core just because the programmer used one or two operations on the type is worse than useless.

Support for Object-Oriented programming

The basic support a programmer needs to write object-oriented programs consists of a class mechanism with inheritance and a mechanism that allows calls of member functions to depend on the actual type of an object (in cases where the actual type is unknown at compile time). The design of the member function calling mechanism is critical. In addition, facilities supporting data abstraction techniques (as described above) are important because the arguments for data abstraction and for its refinements to support elegant use of types are equally valid where support for object-oriented programming is available. The success of both techniques hinges on the design of types and on the ease, flexibility, and efficiency of such types. Object-oriented programming allows user-defined types to be far more flexible and general than the ones designed using only data abstraction techniques.

Calling Mechanisms

The key language facility supporting object-oriented programming is the mechanism by which a member function is invoked for a given object. For example, given a pointer `p`, how is a call `p->f(arg)` handled? There is a range of choices.

In languages such as C++ and Simula, where static type checking is extensively used, the type system can be employed to select between different calling mechanisms. In C++, two alternatives are available:

[1] A normal function call: the member function to be called is determined at compile time (through a lookup in the compiler's symbol tables) and called using the standard function call mechanism with an argument added to identify the object for which the function is called. Where the "standard function call" is not considered efficient enough, the programmer can declare a function `inline` and the compiler will attempt to inline expand its body. In this way, one can achieve the efficiency of a macro expansion without compromising the standard function semantics. This optimization is equally valuable as a support for data abstraction.

[2] A virtual function call: The function to be called depends on the type of the object for which it is called. This type cannot in general be determined until run time. Typically, the pointer `p` will be of some base class `B` and the object will be an object of some derived class `D` (as was the case with the base class `shape` and the derived class `circle` above). The call mechanism must look into the object and find some information placed there by the compiler to determine which function `f` is to be called. Once that function is found, say `D::f`, it can be called using the mechanism described above. The name `f` is converted at compile time into an index into a table of pointers to functions.

This virtual call mechanism can be made essentially as efficient as the "normal function call" mechanism. In the standard C++ implementation, only five additional memory references are used.

In languages with weak static type checking a more elaborate mechanism must be employed. What is done in a language like Smalltalk is to store a list of the names of all member functions (methods) of a class so that they can be found at run time:

[3] A method invocation: First the appropriate table of method names is found by examining the object pointed to by `p`. In this table (or set of tables) the string `f` is looked up to see if the object has an `f()`. If an `f()` is found it is called; otherwise some error handling takes place. This lookup differs from the lookup done at compile time in a statically checked language in that the method invocation uses a method table for the actual object.

A method invocation is inefficient compared with a virtual function call, but more flexible. Since static type checking of arguments typically cannot be done for a method invocation, the use of methods must be supported by dynamic type checking.

Type Checking

The shape example showed the power of virtual functions. What, in addition to this, does a method invocation mechanism do for you? You can attempt to invoke *any* method for *any* object.

The ability to invoke any method for any object enables the designer of general purpose libraries to push the responsibility for handling types onto the user. Naturally this simplifies the design of libraries. However, it then becomes the responsibility of the user to avoid type mismatches like this:

```
// assume dynamic type checking.
// *** NOT C++ ***

Stack s;  // Stack can hold pointers to objects of any type

cs.push(new Saab900);
cs.push(new Saab37B);

cs.pop()->takeoff();    // fine: a Saab37B is a plane

cs.pop()->takeoff();    // Oops! Run time error: a Saab 900 is a car
                        // a car does not have a takeoff method.
```

An attempt to use a `car` as a `plane` will be detected by the message handler and an appropriate error handler will be called. However, that is only a consolation when the user is also the programmer. The absence of static type checking makes it difficult to guarantee that errors of this class are not present in systems delivered to end-users.

Combinations of parameterized classes and the use of virtual functions can approach the flexibility, ease of design, and ease of use of libraries designed with method lookup without relaxing the static type checking or incurring significant run time overheads (in time or space). For example:

```
stack<plane*> cs;

cs.push(new Saab900);      // Compile time error:
                           // type mismatch: car* passed, plane* expected
cs.push(new Saab37B);

cs.pop()->takeoff();      // fine: a Saab 37B is a plane
cs.pop()->takeoff();
```

The use of static type checking and virtual function calls leads to a somewhat different style of programming than does dynamic type checking and method invocation. For example, a Simula or C++ class specifies a fixed interface to a set of objects (of any derived class) whereas a Smalltalk class specifies an initial set of operations for objects (of any subclass). In other words, a Smalltalk class is a minimal specification and the user is free to try operations not specified, whereas a C++ class is an exact specification and the user is guaranteed that only operations specified in the class declaration will be accepted by the compiler.

Inheritance

Consider a language having some form of method lookup without having an inheritance mechanism. Could that language be said to support object-oriented programming? I think not. Clearly, you could do interesting things with the method table to adapt the objects' behavior to suit conditions. However, to avoid chaos, there must be some systematic way of associating methods and the data structures they assume for their object representation. To enable a user of an object to know what kind of behavior to expect, there would also have to be some standard way of expressing what is common to the different behaviors the object might adopt. This "systematic and standard way" would be an inheritance mechanism.

Consider a language having an inheritance mechanism without virtual functions or methods. Could that language be said to support object-oriented programming? I think not: the shape example does not have a good solution in such a language. However, such a language would be noticeably more powerful than a "plain" data abstraction language. This contention is supported by the observation that many Simula and C++ programs are structured using class hierarchies without virtual functions. The ability to express commonality (factoring) is an extremely powerful tool. For example, the problems associated with the need to have a common representation of all shapes could be solved. No union would be needed. However, in the absence of virtual functions, the programmer would have to resort to the use of "type fields" to determine actual types of objects, so the problems with the lack of modularity of the code would remain.[6]

This implies that class derivation (subclassing) is an important programming tool in its own right. It can be used to support object-oriented programming, but it has wider uses. This is particularly true if one identifies the use of inheritance in object-oriented programming with the idea that a base class expresses a general concept of which all derived classes are specializations. This idea captures only part of the expressive power of inheritance, but it is strongly encouraged by languages where every member function is virtual (or a method). Given suitable controls of what is inherited (see Stroustrup, B., *The C++ Programming Language*, Addison-Wesley, 1986. 2nd Edition 1991.), class derivation can be a powerful tool for creating new types. Given a class, derivation can be used to add and/or subtract features. The relation of the resulting class to its base cannot always be completely described in terms of specialization; factoring may be a better term.

Derivation is another tool in the hands of a programmer and there is no foolproof way of predicting how it is going to be used – and it is too early (even after almost 25 years of Simula) to tell which uses are simply mis-uses.

Multiple Inheritance

When a class A is a base of class B, a B inherits the attributes of an A; that is, a B is an A in addition to whatever else it might be. Given this explanation it seems obvious that it might be useful to have a class B inherit from two base classes A1 and A2. This is called multiple inheritance.

A fairly standard example of the use of multiple inheritance would be to provide two library classes displayed and task for representing objects under the control of a display manager and co-routines under the control of a scheduler, respectively. A programmer could then create classes such as

```
class my_displayed_task : public displayed, public task {
    // my stuff
};

class my_task : public task {  // not displayed
    // my stuff
};

class my_displayed : public displayed {  // not a task
    // my stuff
};
```

Using (only) single inheritance only two of these three choices would be open to the programmer. This leads to either code replication or loss of flexibility – and typically both. In C++ this example can be handled as shown above with to no significant overheads (in time or space) compared to single inheritance and without sacrificing static type checking.

Ambiguities are handled at compile time:

```
class A { public: void f(); /* ... */ };
class B { public: void f(); /* ... */ };
class C : public A, public B { /* ... */ };

void g(C* p)
{
        p->f();       // error: ambiguous
}
```

In this, C++ differs from the object-oriented Lisp dialects that support multiple inheritance. In these Lisp dialects ambiguities are resolved by considering the order of declarations significant, by considering objects of the same name in different base classes identical, or by combining methods of the same name in base classes into a more complex method of the highest class.

In C++, one would typically resolve the ambiguity by adding a function:

```
class C : public A, public B {
      // ...
public:
      void f();
      // ...
};

void f()
{
      // C's own stuff
      A::f();
      B::f();
}
```

In addition to this straightforward concept of independent multiple inheritance there appears to be a need for a more general mechanism for expressing dependencies between classes in a multiple inheritance lattice. In C++, the requirement that a sub-object should be shared by all other sub-objects in a class object is expressed through the mechanism of a virtual base class:

```
class W { /* ... */ }; // window

class Bwindow: public virtual W { // window with border
      // ...
};

class Mwindow : public virtual W { // window with menu
      // ...
};

class BMW : public Bwindow, public Mwindow {
      // window with border and menu
      // ...
};
```

Here the (single) `window` sub-object is shared by the `Bwindow` and `Bwindow` sub-objects of a `BMW`. The Lisp dialects provide concepts of method combination to ease programming using such complicated class hierarchies. C++ does not.

Encapsulation

Consider a class member (either a data member or a function member) that needs to be protected from "unauthorized access." What choices can be reasonable for delimiting the set of functions that may access that member? The "obvious" answer for a language supporting object-oriented programming is "all operations defined for this object," that is, all member functions. A non-obvious implication of this answer is that there cannot be a complete and final list of all functions that may access the protected member since one can always add another by deriving a new class from the protected member's class and define a member function of that derived class. This approach combines a large degree of protection from accident (since you do not easily define a new derived class "by accident") with the flexibility needed for "tool building" using class hierarchies (since you can "grant yourself access" to protected members by deriving a class). For example:

```
class Window {
        // ...
protected:
        Rectangle inside;
        // ...
public:
        // ...
};

class Dumb_terminal : Window {
        // ...
public:
        void prompt();
        // ...
};
```

Here `Window` specifies `inside` as protected so that derived classes such as `Dumb_terminal` can read it and figure out what part of the `Window`'s area it may manipulate.

Unfortunately, the "obvious" answer for a language oriented towards data abstraction is different: "list the functions that need access in the class declaration." There is nothing special about these functions. In particular, they need not be member functions. A non-member function with access to private class members is called a `friend` in C++. Class `complex` above was defined using `friend` functions. It is sometimes important that a function may be specified as a `friend` in more than one class. Having the full list of members and friends available is a great advantage when you are trying to understand the behavior of a type and especially when you want to modify it.

Encapsulation issues increase dramatically in importance with the size of the program and with the number and geographical dispersion of its users. (See *The C++ Programming Language* for more detailed discussions of language support for encapsulation.)

Implementation Issues

The support needed for object-oriented programming is primarily provided by the run-time system and by the programming environment. Part of the reason is that object-oriented programming builds on the language improvements already pushed to their limit to support data abstraction so that relatively few additions are needed.[7]

The use of object-oriented programming blurs the distinction between a programming language and its environment further. Since more powerful special- and general-purpose user-defined types can be defined, their use pervades user programs. This requires further development of both the run-time system, library facilities, debuggers, performance measuring, monitoring tools, etc. Ideally these are integrated into a unified programming environment. Smalltalk is the best example of this.

Limits to Perfection

A major problem with a language defined to exploit the techniques of data hiding, data abstraction, and object-oriented programming is that to claim to be a general purpose programming language it must

1. Run on traditional machines.
2. Coexist with traditional operating systems.
3. Compete with traditional programming languages in terms of run time efficiency.
4. Cope with every major application area.

This implies that facilities must be available for effective numerical work (floating point arithmetic without overheads that would make Fortran appear attractive), and that facilities must be available for access to memory in a way that allows device drivers to be written. It must also be possible to write calls that conform to the often rather strange standards required for traditional operating system interfaces. In addition, it should be possible to call functions written in other languages from an object-oriented programming language and for functions written in the object-oriented programming language to be called from a program written in another language.

Another implication is that an object-oriented programming language cannot completely rely on mechanisms that cannot be efficiently implemented on a traditional architecture and still expect to be used as a general purpose language. A very general implementation of method invocation can be a liability unless there are alternative ways of requesting a service.

Similarly, garbage collection can become a performance and portability bottleneck. Most object-oriented programming languages employ garbage collection to simplify the task of the programmer and to reduce the complexity of the language and its compiler. However, it ought to be possible to use garbage collection in non-critical areas while retaining control of storage use in areas where it matters. As an alternative, it is feasible to have a language without garbage collection and then provide sufficient expressive power to enable the design of types that maintain their own storage. C++ is an example of this.

Exception handling and concurrency features are other potential problem areas. Any feature that is best implemented with help from a linker can become a portability problem.

The alternative to having "low level" features in a language is to handle major application areas using separate "low level" languages.

Conclusions

Object-oriented programming is programming using inheritance. Data abstraction is programming using user-defined types. With few exceptions, object-oriented programming can and ought to be a superset of data abstraction. These techniques need proper support to be effective. Data abstraction primarily needs support in the form of language features and object-oriented programming needs further support from a programming environment. To be general purpose, a language supporting data abstraction or object-oriented programming must enable effective use of traditional hardware.

Footnotes

1. I prefer the term "user defined type": *"Those types are not "abstract"; they are as real as* `int` *and* `float`." — Doug McIlroy. An alternative definition of *abstract data types* would require a mathematical "abstract" specification of all types (both built-in and user-defined). What are referred to as types in this paper would, given such a specification, be concrete specifications of such truly abstract entities.
2. However, more advanced mathematics may benefit from the use of inheritance: fields are specializations of rings; vector spaces a special case of modules.
3. The ANSI C++ committee, X3J16, only accepted templates into C++ in July 1990, so few C++ implementations support templates at the time of writing.
4. The ANSI C++ committee, X3J16, only accepted exception handling into C++ in November 1990, so C++ implementations that support exception handling are rare at the time of writing.
5. This style also relies on the existence of a distinguished value to represent "end of iteration." Often, in particular for C++ pointer types, `0` can be used.
6. This is the problem with Simula's `inspect` statement and the reason it does not have a counterpart in C++.
7. This assumes that an object-oriented language does indeed support data abstraction. However, the support for data abstraction is often deficient in such languages. Conversely, languages that support data abstraction are typically deficient in their support of object-oriented programming.

5 Multiple Inheritance

Multiple Inheritance for C++

NOTE

This chapter is taken directly from a paper by Bjarne Stroustrup.

Abstract

Multiple Inheritance is the ability of a class to have more than one base class (super class). In a language where multiple inheritance is supported a program can be structured as a set of inheritance lattices instead of (just) as a set of inheritance trees. This is widely believed to be an important structuring tool. It is also widely believed that multiple inheritance complicates a programming language significantly, is hard to implement, and is expensive to run. I will demonstrate that none of these last three conjectures are true.

Introduction

This paper describes an implementation of a multiple inheritance mechanism for C++ (described in *The C++ Programming Language*). It provides only the most rudimentary explanation of what multiple inheritance is in general and what it can be used for. The particular variation of the general concept implemented here is primarily explained in terms of this implementation.[1]

First a bit of background on multiple inheritance and C++ implementation technique is presented, then the multiple inheritance scheme implemented for C++ is introduced in two stages:

- the basic scheme for multiple inheritance, the basic strategy for ambiguity resolution, and the way to implement virtual functions
- handling of classes included more than once in an inheritance lattice; the programmer has the choice whether a multiply included base class will result in one or more sub-objects being created

Finally, some the complexities and overheads introduced by this multiple inheritance scheme are summarized.

Multiple Inheritance

Consider writing a simulation of a network of computers. Each node in the network is represented by an object of class `Switch`, each user or computer by an object of class `Terminal`, and each communication line by an object of class `Line`. One way to monitor the simulation (or a real network of the same structure) would be to display the state of objects of various classes on a screen. Each object to be displayed is represented as an object of class `Displayed`. Objects of class `Displayed` are under control of a display manager that ensures regular update of a screen and/or data base. The classes `Terminal` and `Switch` are derived from a class `Task` that provides the basic facilities for co-routine style behavior. Objects of class `Task` are under control of a task manager (scheduler) that manages the real processor(s).

Ideally `Task` and `Displayed` are classes from a standard library. If you want to display a terminal class `Terminal` must be derived from class `Displayed`. Class `Terminal`, however, is already derived from class `Task`. In a single inheritance language, such as C++ or Simula67, we have only two ways of solving this problem: deriving `Task` from `Displayed` or deriving `Displayed` from `Task`. Neither is ideal since they both create a dependency between the library versions of two fundamental and independent concepts. Ideally one would want to be able to choose between saying that a `Terminal` is a `Task` *and* a `Displayed`; that a `Line` is a `Displayed` *but not* a `Task`; and that a `Switch` is a `Task` *but not* a `Displayed`.

The ability to express this using a class hierarchy, that is, to derive a class from more than one base class, is usually referred to as *multiple inheritance*. Other examples involve the representation of various kinds of windows in a window system and the representation of various kinds of processors and compilers for a multi-machine, multi-environment debugger.

In general, multiple inheritance allows a user to combine independent (and not so independent) concepts represented as classes into a composite concept represented as a derived class. A common way of using multiple inheritance is for a designer to provide sets of base classes with the intention that a user creates new classes by choosing base classes from each of the relevant sets. Thus a programmer creates new concepts using a recipe like "pick an A and/or a B." In the window example, a user might specify a new kind of window by selecting a style of window interaction (from the set of interaction base classes) and a style of appearance (from the set of base classes defining display options). In the debugger example, a programmer would specify a debugger by choosing a processor and a compiler.

Given multiple inheritance and N concepts each of which might somehow be combined with one of M other concepts, we need N+M classes to represent all the combined concepts. Given only single inheritance, we need to replicate information and provide N+M+N*M classes. Single inheritance handles cases where N==1 or M==1. The usefulness of multiple inheritance for avoiding replication hinges on the importance of examples where the values of N and M are both larger than 1. It appears that examples with N>=2 and M>=2 are not uncommon; the window and debugger examples described above will typically have both N and M larger than 2.

C++ Implementation Strategy

Before discussing multiple inheritance and its implementation in C++ I will first describe the main points in the traditional implementation of the C++ single inheritance class concept.

An object of a C++ class is represented by a contiguous region of memory. A pointer to an object of a class points to the first byte of that region of memory. The compiler turns a call of a member function into an "ordinary" function call with an "extra" argument; that "extra" argument is a pointer to the object for which the member function is called.

Consider a simple class `A`:[2]

```
class A {
        int a;
        void f(int i);
};
```

An object of class A will look like this

```
-----------------
|    int a;      |
-----------------
```

No information is placed in an `A` except the integer `a` specified by the user. No information relating to (non-virtual) member functions is placed in the object.

A call of the member function `A::f`:

```
A* pa;
pa->f(2);
```

is transformed by the compiler into an "ordinary function call":

```
f__F1A(pa,2);
```

Objects of derived classes are composed by concatenating the members of the classes involved:

```
class A { int a; void f(int); };
class B : A { int b; void g(int); };
class C : B { int c; void h(int); };
```

Again, no "housekeeping" information is added, so an object of class `C` looks like this:

```
-----------------
|    int a;      |
|    int b;      |
|    int c;      |
-----------------
```

The compiler "knows" the position of all members in an object of a derived class exactly as it does for an object of a simple class and generates the same (optimal) code in both cases.

Implementing virtual functions involves a table of functions. Consider:

```
class A {
        int a;
        virtual void f(int);
        virtual void g(int);
        virtual void h(int);
};


class B : A { int b; void g(int); };
class C : B { int c; void h(int); };
```

In this case, a table of virtual functions, the `vtbl`, contains the appropriate functions for a given class and a pointer to it is placed in every object. A class `C` object looks like this:

```
-----------------
|    int a;      |        vtbl:
|      vptr .........> -----------------
|    int b;      |        |     A::f       |
|    int c;      |        |     B::g       |
-----------------         |     C::h       |
                          -----------------
```

A call to a virtual function is transformed into an indirect call by the compiler. For example,

```
C* pc;
pc->g(2);
```

becomes something like:

```
(*(pc->vptr[1]))(pc,2);
```

A multiple inheritance mechanism for C++ must preserve the efficiency and the key features of this implementation scheme.

Multiple Base Classes

Given two classes

```
class A { ... };
class B { ... };
```

one can design a third using both as base classes:

```
class C : A , B { ... };
```

This means that a `C` is an `A` and a `B`. One might equivalently[3] define `C` like this:

```
class C : B , A { ... };
```

Object Layout

An object of class `C` can be laid out as a contiguous object like this:

```
-----------------
|               |
|    A part     |
|               |
-----------------
|               |
|    B part     |
|               |
-----------------
|               |
|    C part     |
|               |
-----------------
```

Accessing a member of classes `A`, `B` or `C` is handled exactly as before: the compiler knows the location in the object of each member and generates the appropriate code (without spurious indirections or other overhead).

Member Function Call

Calling a member function of `A` or `C` is identical to what was done in the single inheritance case. Calling a member function of `B` given a `C*` is slightly more involved:

```
C* pc;
pc->bf(2);          // assume that bf is a member of B
                    // and that C has no member named bf
                    // except the one inherited from B
```

Naturally, `B::bf()` expects a `B*` (to become its `this` pointer). To provide it, a constant must be added to pc. This constant, `delta(B)`, is the relative position of the `B` part of `C`. This delta is known to the compiler that transforms the call into:

```
bf__F1B((B*)((char*)pc+delta(B)),2);
```

The overhead is one addition of a constant per call of this kind. During the execution of a member function of `B` the function's `this` pointer points to the `B` part of `C`:

```
pc ..................> ----------------
                       |              |
                       |    A part    |
                       |              |
B::bf's this ........> ----------------
                       |              |
                       |    B part    |
                       |              |
                       ----------------
                       |              |
                       |    C part    |
                       |              |
                       ----------------
```

Note that there is no space penalty involved in using a second base class and that the minimal time penalty is incurred only once per call.

Ambiguities

Consider potential ambiguities if both `A` and `B` have a public member `ii`:

```
class A { int ii; };
class B { char* ii; };
class C : A, B { };
```

In this case `C` will have two members called `ii`, `A::ii` and `B::ii`. Then

```
C* pc;
pc->ii;             // error: A::ii or B::ii ?
```

is illegal since it is ambiguous. Such ambiguities can be resolved by explicit qualification:

```
pc->A::ii;          // C's A's ii
pc->B::ii;          // C's B's ii
```

A similar ambiguity arises if both `A` and `B` have a function `f()`:

```
class A { void f(); };
class B { int f(); };
class C : A, B { };

C* pc;
pc->f();            // error: A::f or B::f ?

pc->A::f();         // C's A's f
pc->B::f();         // C's B's f
```

As an alternative to specifying which base class in each call of an `f()`, one might define an `f()` for `C`.

`C::f()` might call the base class functions. For example:

```
class C : A, B {
        int f() { A::f(); return B::f(); }
};

C* pc;
pc->f();            // C::f is called
```

Casting

Explicit and implicit casting may also involve modifying a pointer value with a delta:

```
C* pc;
B* pb;
pb = (B*)pc;        // pb = (B*)((char*)pc+delta(B))
pb = pc;            // pb = (B*)((char*)pc+delta(B))
pc = pb;            // error: cast needed
pc = (C*)pb;        // pc = (C*)((char*)pb-delta(B))
```

Casting yields the pointer referring to the appropriate part of the same object.

```
pc ...> -----------------
        |               |
        |     A part    |
        |               |
pb ...> -----------------
        |               |
        |     B part    |
        |               |
        -----------------
        |               |
        |     C part    |
        |               |
        -----------------
```

Comparisons are interpreted in the same way:

```
pc == pb;           // that is, pc == (C*)pb
                    //          or equivalently (B*)pc == pb

                    // that is, (B*)((char*)pc+delta(B)) == pb
                    //          or equivalently pc == (C*)((char*)pb-delta(B))
```

Note that in both C and C++ casting has always been an operator that produced one value given another rather than an operator that simply reinterpreted a bit pattern. For example, on almost all machines `(int).2` causes code to be executed; `(float)(int).2` is not equal to `.2`. Introducing multiple inheritance as described here will introduce cases where `(char*)(B*)v!=(char*)v` for some pointer type `B*`. Note, however, that when B is a base class of C, (B*)v==(C*)v==v.

Zero Valued Pointers

Pointers with the value zero cause a separate problem in the context of multiple base classes. Consider applying the rules presented above to a zero-valued pointer:

```
C* pc = 0;
B* pb = 0;
if (pb == 0) ...
pb = pc;           // pb = (B*)((char*)pc+delta(B))
if (pb == 0) ...
```

The second test would fail since pb would have the value (B*)((char*)0+delta(B)).

The solution is to elaborate the conversion (casting) operation to test for the pointer-value 0:

```
C* pc = 0;
B* pb = 0;
if (pb == 0) ...
pb = pc;           // pb = (pc==0)?0:(B*)((char*)pc+delta(B))
if (pb == 0) ...
```

The added complexity and run-time overhead are a test and an increment.

Virtual Functions

Naturally, member functions may be virtual:

```
class A { virtual void f(); };
class B { virtual void f(); virtual void g(); };
class C : A , B { void f(); };

A* pa = new C;
B* pb = new C;
C* pc = new C;

pa->f();
pb->f();
pc->f();
```

All these calls will invoke C::f(). This follows directly from the definition of virtual since class C is derived from class A and from class B.

Implementation

On entry to `C::f`, the `this` pointer must point to the beginning of the `C` object (and not to the `B` part). However, it is not in general known at compile time that the `B` pointed to by `pb` is part of a `C` so the compiler cannot subtract the constant `delta(B)`. Consequently `delta(B)` must be stored so that it can be found at run time. Since it is only used when calling a virtual function the obvious place to store it is in the table of virtual functions (`vtbl`). For reasons that will be explained below the delta is stored with each function in the `vtbl` so that a `vtbl` entry will be of the form:

```
struct vtbl_entry {
        void     (*fct)();
        int      delta;
};
```

An object of class `C` will look like this:

```
        -----------------
        |               |       vtbl:
        |      vptr ..........>---------------------
        |      A part   |       | C::f |     0     |
        |               |       ---------------------
        -----------------
        |               |       vtbl:
        |      vptr ..........>---------------------
        |      B part   |       | C::f | -delta(B) |
        |               |       | B::g |     0     |
        -----------------       ---------------------
        |               |
        |      C part   |
        |               |
        -----------------
```

```
pb->f();          // call of C::f:
                  // register vtbl_entry* vt = &pb->vtbl[index(f)];
                  // (*vt->fct)((B*)((char*)pb+vt->delta))
```

Note that the object pointer may have to be adjusted to point to the correct sub-object before looking for the member pointing to the `vtbl`. Note also that each combination of base class and derived class has its own `vtbl`. For example, the `vtbl` for `B` in `C` is different from the `vtbl` of a separately allocated `B`. This implies that in general an object of a derived class needs a `vtbl` for each base class plus one for the derived class. However, as with single inheritance, a derived class can share a `vtbl` with its first base so that in the example above only two `vtbls` are used for an object of type `C` (one for `A` in `C` combined with `C`'s own plus one for `B` in `C`).

Using an `int` as the type of a stored delta limits the size of a single object; that might not be a bad thing.

Ambiguities

The following demonstrates a problem:

```
class A { virtual void f(); };
class B { virtual void f(); };
class C : A , B { void f(); };

C* pc = new C;

pc->f();

pc->A::f();
pc->B::f();
```

Explicit qualification "suppresses" `virtual` so the last two calls really invoke the base class functions. Is this a problem? Usually, no. Either `C` has an `f()` and there is no need to use explicit qualification or `C` has no `f()` and the explicit qualification is necessary and correct. Trouble can occur when a function `f()` is added to `C` in a program that already contains explicitly qualified names. In the latter case one could wonder why someone would want to both declare a function virtual and also call it using explicit qualification. If `f()` is virtual, adding an `f()` to the derived class is clearly the correct way of resolving the ambiguity.

The case where no `C::f` is declared cannot be handled by resolving ambiguities at the point of call. Consider:

```
class A { virtual void f(); };
class B { virtual void f(); };
class C : A , B {  };           // error: C::f needed

C* pc = new C;
pc->f();            // ambiguous

A* pa = pc;         // implicit conversion of C* to A*
pa->f();            // not ambiguous: calls A::f();
```

The potential ambiguity in a call of `f()` is detected at the point where the virtual function tables for `A` and `B` in `C` are constructed. In other words, the declaration of `C` above is illegal because it would allow calls, such as `pa->f()`, which are unambiguous *only* because type information has been "lost" through an implicit coercion; a call of `f()` for an object of type `C` is ambiguous.

Multiple Inclusions

A class can have any number of base classes. For example,

```
class A : B1, B2, B3, B4, B5, B6 { ... };
```

It illegal to specify the same class twice in a list of base classes. For example,

```
class A : B, B { ... };          // error
```

The reason for this restriction is that every access to a `B` member would be ambiguous and therefore illegal; this restriction also simplifies the compiler.

Multiple Sub-objects

A class may be included more than once as a base class. For example:

```
class L { ... };
class A : L { ... };
class B : L { ... };
class C : A , B { ... };
```

In such cases multiple objects of the base class are part of an object of the derived class. For example, an object of class `C` has two `L`'s: one for `A` and one for `B`:

```
-----------------
|               |
| L part (of A) |
|               |
|  -----------  |
|               |
|    A part     |
|               |
-----------------
|               |
| L part (of B) |
|               |
|  -----------  |
|               |
|    B part     |
|               |
-----------------
|               |
|    C part     |
|               |
-----------------
```

This can even be useful. Think of `L` as a link class for a Simula-style linked list. In this case a `C` can be on both the list of `A`s and the list of `B`s.

Naming

Assume that class `L` in the example above has a member `m`. How could a function `C::f` refer to `L::m`? The obvious answer is "by explicit qualification":

```
void C::f() { A::m = B::m; }
```

This will work nicely provided neither `A` nor `B` has a member `m` (except the one they inherited from `L`). If necessary, the qualification syntax of C++ could be extended to allow the more explicit:

```
void C::f() { A::L::m = B::L::m; }
```

Casting

Consider the example above again. The fact that there are two copies of `L` makes casting (both explicit and implicit) between `L*` and `C*` ambiguous, and consequently illegal:

```
C* pc = new C;
L* pl = pc;          // error: ambiguous
pl = (L*)pc;         // error: still ambiguous
pl = (L*)(A*)pc;     // The L in C's A
pc = pl;             // error: ambiguous
pc = (L*)pl;         // error: still ambiguous
pc = (C*)(A*)pl;     // The C containing A's L
```

I don't expect this to be a problem. The place where this will surface is in cases where `A`s (or `B`s) are handled by functions expecting an `L`; in these cases a `C` will not be acceptable despite a `C` being an `A`:

```
extern f(L*);        // some standard function

A aa;
C cc;

f(&aa);              // fine
f(&cc);              // error: ambiguous
f((A*)&cc);          // fine
```

Casting is used for explicit disambiguation.

Virtual Base Classes

When a class `C` has two base classes `A` and `B` these two base classes give rise to separate sub-objects that do not relate to each other in ways different from any other `A` and `B` objects. I call this *independent multiple inheritance*. However, many proposed uses of multiple inheritance assume a dependence among base classes (for example, the style of providing a selection of features for a window described in this chapter under "Multiple Inheritance"). Such dependencies can be expressed in terms of an object shared between the various derived classes. In other words, there must be a way of specifying that a base class must give rise to only one object in the final derived class even if it is mentioned as a base class several times. To distinguish this usage from independent multiple inheritance such base classes are specified to be virtual:

```
class AW : virtual W { ... };
class BW : virtual W { ... };
class CW : AW , BW { ... };
```

A single object of class `W` is to be shared between `AW` and `BW`; that is, only one `W` object must be included in `CW` as the result of deriving `CW` from `AW` and `BW`. Except for giving rise to a unique object in a derived class, a `virtual` base class behaves exactly like a non-virtual base class.

The "virtualness" of `W` is a property of the derivation specified by `AW` and `BW` and not a property of `W` itself. Every `virtual` base in an inheritance DAG refers to the same object. This object is constructed once using a default constructor. A class that can only be constructed given an argument cannot be a virtual base.

A class may be both a normal and a virtual base in an inheritance DAG:

```
class A : virtual L { ... };
class B : virtual L { ... };
class C : A , B { ... };
class D : L, C { ... };
```

A `D` object will have two sub-objects of class `L`, one virtual and one "normal."

Representation

The object representing a virtual base class `W` object cannot be placed in a fixed position relative to both `AW` and `BW` in all objects. Consequently, a pointer to `W` must be stored in all objects directly accessing the `W` object to allow access independently of its relative position. For example:

```
AW* paw = new AW;
BW* pbw = new BW;
CW* pcw = new CW;


        ----------------
paw ..> |              ...........
        |    AW part    |         .
        |               |         v
        ----------------          .
        |               |<.......
        |    W part     |
        |               |
        ----------------
        -----------------
pbw ..> |              ...........
        |     BW part  |         .
        |              |         v
        -----------------        .
        |              |<.......
        |     W part   |
        |              |
        -----------------

        -----------------
pcw ..> |              ...........
        |     AW part  |         .
        |              |         v
        -----------------        .
        |              ...........
        |     BW part  |         .
        |              |         v
        -----------------        .
        |              |         .
        |     CW part  |         .
        |              |         v
        -----------------        .
        |              |<.......
        |     W part   |
        |              |
        -----------------
```

A class can have an arbitrary number of virtual base classes.

One can cast from a derived class to a virtual base class, but not from a virtual base class to a derived class. The former involves following the virtual base pointer; the latter cannot be done given the information available at run time. Storing a "back-pointer" to the enclosing object(s) is non-trivial in general and was considered unsuitable for C++ as was the alternative strategy of dynamically keeping track of the objects "for which" a given member function invocation operates.

Virtual Functions

Consider:

```
class W {
         virtual void f();
         virtual void g();
         virtual void h();
         virtual void k();
         ...
};

class AW : virtual W { void g(); ... };
class BW : virtual W { void f(); ... };
class CW : AW , BW { void h(); ... };

CW* pcw = new CW;

pcw->f();         // BW::f()
pcw->g();         // AW::g()
pcw->h();         // CW::h()
((AW*)pcw)->f();  // BW::f();
```

A `CW` object might look like this:

```
    -----------------
.........           |
.   |       AW part |
v   |               |
.   -----------------
.........           |
.   |       BW part |
v   |               |
.   -----------------
.   |               |
.   |       CW part |
v   |               |       vtbl:
.   -----------------       ------------------------------
...>|       vptr ..........>| BW::f | delta(BW)-delta(W) |
    |               |       | AW::g |     -delta(W)      |
    |       W part  |       | CW::h |     -delta(W)      |
    |               |       |  W::k |         0          |
    -----------------       ------------------------------
```

In general, the delta stored with a function pointer in a `vtbl` is the delta of the class defining the function minus the delta of the class for which the `vtbl` is constructed.

If `W` has a virtual function `f` that is re-defined in both `AW` and `BW` but not in `CW` an ambiguity results. Such ambiguities are easily detected at the point where `CW`'s `vtbl` is constructed.

The rule for detecting ambiguities in a class lattice, or more precisely a directed acyclic graph (DAG) of classes, is that all re-definitions of a virtual function from a virtual base class must occur on a single path through the DAG. The example above can be drawn as a DAG like this:

```
        ....> W { f g h k } <...
        |                      |
        ^                      ^
        |                      |
       AW { g }               BW { f }
        |                      |
        ^                      ^
        |                      |
        ...<... CW { h } ...>...
```

Note that a call "up" through one path of the DAG to a virtual function may result in the call of a function (re-defined) in another path (as happened in the call `((AW*)pcw)->f()` in the example above).

Constructors and Destructors

Constructors for base classes are called before the constructor for their derived class. Destructors for base classes are called after the destructor for their derived class. Destructors are called in the reverse order of their declaration.

Arguments to base class constructors can be specified like this:

```
class A { A(int); };
class B { B(int); };
class C : A , virtual B {
        C(int a, int b) : A(a) , B(b) { ... }
};
```

Constructors are executed in the order their objects are declared. This rule is applied to members and base classes separately and the base class constructors and applied before the member constructors. When a class has more than one base class *all* argument lists for its base class constructor *must* be qualified with the name of the base class. This rule applies even if only one of the base classes actually requires arguments.

A virtual base is constructed before any of its derived classes. Virtual bases are constructed before any non-virtual bases and in the order they appear on a depth first left-to-right traversal of the inheritance DAG (directed acyclic graph). This rule applies recursively for virtual bases of virtual bases.

A virtual base is initialized by the "most derived" class of which it is a base. For example:

```
class V { public: V(); V(int); /* ... */ };
class A : public virtual V { public: A(); A(int); /* ... */ };
class B : public virtual V { public: B(); B(int); /* ... */ };
class C : public A, public B { public: C(); C(int); /* ... */ };


A::A(int i) : V(i) { /* ... */ }
B::B(int i) { /* ... */ }
C::C(int i) { /* ... */ }


          V v(1);         // use V(int)
          A a(2);         // use V(int)
          B b(3);         // use V()
          C c(4);         // use V()
```

The order of destructor calls is defined to be the reverse order of appearance in the class declaration (members before bases). There is no way for the programmer to control this order — except by the declaration order. A virtual base is destroyed after all of its derived classes.

Assignment to `this` in the constructor of a class that takes part in a multiple inheritance lattice is likely to lead to disaster. See Chapter 1 for alternatives.

Visibility

The examples above ignored visibility considerations. A base class may be `public` or `private`. In addition, it may be `virtual`. For example:

```
class D
          : B1              // private (by default), non-virtual (by default)
          , virtual B2      // private (by default), virtual
          , public B3       // public, non-virtual (by default)
          , public virtual B4 {
          // ...
};
```

Note that a visibility or `virtual` specifier applies to a single base class only. For example,

```
class C : public A, B { ... };
```

declares a public base `A` and a private base `B`.

Overheads

The overhead in using this scheme is:

1. one subtraction of a constant for each use of a member in a base class that is included as the second or subsequent base
2. one word per function in each `vtbl` (to hold the delta)
3. one memory reference and one subtraction for each call of a virtual function
4. one memory reference and one subtraction for access of a base class member of a virtual base class

Note that overheads [1] and [4] are only incurred where multiple inheritance is actually used, but overheads [2] and [3] are incurred for each class with virtual functions and for each virtual function call even when multiple inheritance is not used. Overheads [1] and [4] are only incurred when members of a second or subsequent base are accessed "from the outside"; a member function of a virtual base class does not incur special overheads when accessing members of its class.

This implies that except for [2] and [3] you pay only for what you actually use; [2] and [3] impose a minor overhead on the virtual function mechanism even where only single inheritance is used. This latter overhead could be avoided by using an alternative implementation of multiple inheritance, but I don't know of such an implementation that is also faster in the multiple inheritance case and as portable as the scheme described here.

Fortunately, these overheads are not significant. The time, space, and complexity overheads imposed on the compiler to implement multiple inheritance are not noticeable to the user.

But is it Simple to Use?

What makes a language facility hard to use?

1. Lots of rules.
2. Subtle differences between rules.
3. Inability to automatically detect common errors.
4. Lack of generality.
5. Deficiencies.

The first two cases lead to difficulty of learning and remembering, causing bugs due to misuse and misunderstanding. The last two cases cause bugs and confusion as the programmer tries to circumvent the rules and "simulate" missing features. Case [3] causes frustration as the programmer discovers mistakes the hard way.

The multiple inheritance scheme presented here provides two ways of extending a class's name space:

- a base class
- a virtual base class

These are two ways of creating/specifying a new class rather than ways of creating two different kinds of classes. The rules for using the resulting classes do not depend on how the name space was extended:

- ambiguities are illegal
- rules for use of members are what they were for single inheritance
- visibility rules are what they were for single inheritance
- initialization rules are what they were for single inheritance

Violations of these rules are detected by the compiler.

In other words, the multiple inheritance scheme is only more complicated to use than the existing single inheritance scheme in that

- you can extend a class's name space more than once (with more than one base class)
- you can extend a class's name space in two ways rather than in only one way

This appears minimal and constitutes an attempt to provide a formal and (comparatively) safe set of mechanisms for observed practices and needs. I think that the scheme described here is "as simple as possible, but no simpler."

A potential source of problems exists in the absence of "system provided back-pointers" from a virtual base class to its enclosing object.

In some contexts, it might also be a problem that pointers to sub-objects are used extensively. This will affect programs that use explicit casting to non-object-pointer types (such as `char*`) and "extra linguistic" tools (such as debuggers and garbage collectors). Otherwise, and hopefully normally, all manipulation of object pointers follows the consistent rules explained previously and is invisible to the user.

Conclusions

Multiple inheritance is reasonably simple to add to C++ in a way that makes it easy to use. Multiple inheritance is not too hard to implement, since it requires only very minor syntactic extensions, and fits naturally into the (static) type structure. The implementation is very efficient in both time and space. Compatibility with C is not affected. Portability is not affected.

Footnotes

1. An earlier version of this paper was presented to the European UNIX Users' Group conference in Helsinki, May 1987. This paper has been revised to match the multiple inheritance scheme that was arrived at after further experimentation and thought. For more information see "The Evolution of C++: 1985-1987" and "What is 'Object-Oriented Programming?'."
2. In most of this paper data hiding issues are ignored to simplify the discussion and shorten the examples. This makes some examples illegal. Changing the word `class` to `struct` would make the examples legal, as would adding `public` specifiers in the appropriate places.
3. This definition is equivalent except for possible side effects in constructors and destructors (access to global variables, input operations, output operations, etc.).

6 Parameterized Types

Parameterized Types for C++

NOTE This chapter is taken directly from a paper by Bjarne Stroustrup.

Abstract

Type parameterization is the ability to define a type in terms of another, unspecified, type. Versions of the parameterized type may then be created for several particular parameter types. A language supporting type parameterization allows specification of general container types such as *list*, *vector*, and *associative array* where the specific type of the elements is left as a parameter. Thus, a parameterized class specifies an unbounded set of related types; for example: list of int, list of name, list of shape, etc. Type parameterization is one way of making a language more extensible.

In the context of C++, the problem are

[1] Can type parameterization be easy to use?
[2] Can objects of a parameterized type be used as efficiently as objects of a "hand-coded" type?
[3] Can a general form of parameterized types be integrated into C++?
[4] Can parameterized types be implemented so that the compilation and linking speed is similar to that achieved by a compilation system that does not support type parameterization?
[5] Can such a compilation system be simple and portable?

A design is presented for which the answer to all of these questions is *yes*. The implementation of this scheme is a fairly simple extension of current C++ implementations.

WARNING: The scheme for providing parameterized types described here is not implemented. It is not part of the C++ language, nor is there any guarantee that it ever will be. This paper was written to stimulate and focus discussion about the usefulness of a parameterized type facility for C++ and about the possible forms such a facility might take.

Introduction

For many people, the largest single problem using C++ is the lack of an extensive standard library. A major problem in producing such a library is that C++ does not provide a sufficiently general facility for defining "container classes" such as lists, vectors, and associative arrays. There are two approaches for providing such classes/types:

[1] The Smalltalk approach: rely on dynamic typing and inheritance.

[2] The Clu approach: rely on static typing and a facility for arguments of type *type*.

The former is very flexible, but carries a high run-time cost, and more importantly defies attempts to use static type checking to catch interface errors. The latter approach has traditionally given rise to fairly complicated language facilities and also to slow and elaborate compile/link time environments. This approach also suffered from inflexibility because languages where it was used, notably Ada, had no inheritance mechanism.

Ideally we would like a mechanism for C++ that is as structured as the Clu approach with ideal run-time and space requirements, and with low compile-time overheads. It also ought to be as flexible as Smalltalk's mechanisms. The former is possible; the latter can be approximated for many important cases.

Note that C++ appears to have sufficient expressive power to cope with the demands of library writing provided there is a single basic kind of object, such as a character (for string manipulation, pattern matching, character I/O, etc.), a double precision floating point number (for engineering libraries), or a bitmap (for graphics libraries). The "container class problem" is particularly serious, though, since container classes are needed to specify all but the simplest interfaces; they are the "glue" for larger systems.

Class Templates

A C++ parameterized type will be referred to as a class template. A class template specifies how individual classes can be constructed much like the way a class specifies how individual objects can be constructed. A vector class template might be declared like this:

```
template<class T> class vector {
        T* v;
        int sz;
public:
        vector(int);
        T& operator[](int);
        T& elem(int i) { return v[i]; }
        // ...
};
```

The `template <class T>` prefix specifies that a template is being declared and that an argument `T` of type *type* will be used in the declaration. After its introduction, `T` is used exactly like other type names within the scope of the template declaration. Vectors can then be used like this:

```
vector<int> v1(20);
vector<complex> v2(30);

typedef vector<complex> cvec;    // make cvec a synonym for vector<complex>
cvec v3(40);                     // v2 and v3 are of the same type

v1[3] = 7;
v2[3] = v3.elem(4) = complex(7,8);
```

Clearly class templates are no harder to use than classes. The complete names of instances of a class template, such as `vector<int>` and `vector<complex>`, are quite readable. They might even be considered more readable than the notation for the built-in array type: `int[]` and `complex[]`. When the full name is considered too long, abbreviations can be introduced using `typedef`.

It is only trivially more complicated to declare a class template than it is to declare a class. The keyword `class` is used to indicate arguments of type *type* partly because it appears to be an appropriate word, partly because it saves introducing a new keyword. In this context, `class` means "any type" and not just "some user-defined type."

The `<...>` brackets are used in preference to the parentheses `(...)` partly to emphasize the different nature of template arguments (they will be evaluated at compile time) and partly because parentheses are already hopelessly overused in C++.

The keyword `template` is introduced to make template declarations easy to find, for humans and for tools, and to provide a common syntax for class templates and function templates.

Member Function Templates

The operations on a class template must also be defined. This implies that in addition to class templates, we need function templates. For example:

```
template<class T> T& vector<T>::operator[](int i)
{
        if (i<0 || sz<=i) error("vector: range error");
        return v[i];
}
```

A function template is a specification of a family of functions; `template<class T>` specifies that `T` is a template argument (of type *type*) that must somehow be supplied to specify a particular function.

Note that you don't usually have to specify the template arguments to use a function template. For example, the template argument for `vector<T>::operator[]` will be determined by the vector to which the subscripting operation is applied:

```
vector<int> v1(20);
vector<complex> v2(30);

v1[3] = 7;            // vector<int>::operator[]()
v2[3] = complex(7,8);      // vector<complex>::operator[]()
```

Member functions of a class template are themselves function templates with the template arguments specified in the class templates. Function templates and member function templates will be discussed in greater detail below.

Outline of an Implementation

The basic idea for an implementation that incurs no additional costs in run-time or space compared with "hand coding" is to "macro-expand" a template for each different set of template arguments with which it is used. Naturally, template expansion is not really just macro expansion; it obeys proper scope and syntax rules. Names such as `vector<int>` can be encoded into composite class names such as `__PTvector_int`.

The example above expands into:

```
class __PTvector_int {
        int* v;
        int sz;
public:
        __PTvector_int(int);
        int& operator[](int);
        int& elem(int i) { return v[i]; }
        // ...
};

class __PTvector_complex {
        complex* v;
        int sz;
public:
        __PTvector_complex(int);
        complex& operator[](int);
        complex& elem(int i) { return v[i]; }
        // ...
};

__PTvector_int v1(20);
__PTvector_complex v2(30);
__PTvector_complex v3(40);

v1[3] = 7;
v2[3] = v3.elem(4) = complex(7,8);
```

A compiler need not have a separate template expansion pass. Since the information to do such an expansion exists in the compiler's tables, the appropriate actions can simply be taken at the proper places in the analysis and code generation process.

In addition to this expansion mechanism, a facility is needed for detecting which member functions have been used for which instances of a parameterized type. The example above used:

```
__PTvector_int::__PTvector_int();               // constructor
__PTvector_complex::__PTvector_complex();       // constructor
__PTvector_int::operator[]();                   // subscripting
__PTvector_complex::operator[]();               // subscripting
__PTvector_complex::elem();
```

Note that the full list of such functions for a program can be known only after examining every source file. The linker provides a form of this list as part of its list of undefined objects and functions.

The definition of an operation on a class template might look like this:

```
template<class T> T& vector<T>::operator[](int i)
{
        if (i<0 || sz<=i) error("vector: range error");
        return v[i];
}
```

From this, the following two function definitions will have to be generated:

```
int& __PTvector_int::operator[](int i)
{
        if (i<0 || sz<=i) error("vector: range error");
        return v[i];
}

complex& __PTvector_complex::operator[](int i)
{
        if (i<0 || sz<=i) error("vector: range error");
        return v[i];
}
```

This approach ensures that no run-time efficiency is lost compared to "hand-coding". Code space might wasted by creating separate copies of functions that could have shared implementation. For example, `vector<int>` and `vector<unsigned>` need not have separate subscripting operations. Such waste can, if necessary, be reduced through suitable coding practices (see the section on Type Equivalence, below) and/or through a clever compile time environment.

A programmer can provide a definition for a particular version of an operation on a class by specifying the template argument(s) in a function definition:

```
int& vector<int>::operator[](int i) { return v[i]; }
```

The general version of such a function as defined by its template will be used to create a function for a particular argument type only when no user-provided version is specified for that type.

Replacing the default implementation of a function as defined by a template is useful where implementations with greater precision, higher efficiency, etc. can be provided given some understanding of a particular type. It may also be useful for debugging and for supplying different versions of a function to different parts of a program (using `static` functions).

Some Design Considerations

Let us consider a few choices that were made to write the example above:

[1] Should all template arguments be of type *type*?

[2] Should a user be required to specify the set of operations that may be used for a template argument of type *type*?

[3] Should a user be required to explicitly declare what versions of a template can be used in a program?

[4] Should it be possible for a user to declare variables of type *type*?

The answer to all (in the context of C++) is *no*. Let us examine them in turn.

Template Arguments

"Should all template arguments be of type *type*?" No, there appear to be useful examples of type parameters of "normal" types. For example, a vector template might be parameterized with an error handling function:

```
typedef void (*PF)(char*);

template<class T, PF error> class vector {
        T* V;
        int sz;
public:
        T& operator[](int i) {
                if (i<= || sz<=i) error("vector: range error");
                return v[i];
        }
};

void my_error_fct() { ... }
vector<complex,&my_error_fct> v(10);
```

This example implies that default arguments might be useful:

```
template <class T, PF error=&standard_error_fct> class vector { ... }
```

Another example is a buffer type with a size argument:

```
template<class T, int sz=128> class buffer {
        T v[sz];
        // ...
};
```

```
void f()
{
        buffer<char> buf1;
        buffer<complex,20> buf2;
        // ...
}

buffer<char*,1000> glob;
```

Making `sz` an argument of the template `buffer` itself rather than of its objects implies that the size of a `buffer` is known at compile time so that a `buffer` can be allocated without use of free store. It appears that default arguments will be at least as useful for template arguments as they are for ordinary arguments. Default arguments of type *type* might even be useful:

```
template<class T, class TEMP = double> class store {
        // ...
        T sum() { TEMP sum = 0; ... return sum; }
};

store<int,long> istore;
store<float> fstore;
```

These examples demonstrate that the range of templates with which a type can be parameterized should be restricted only if there are compelling arguments that the restriction will significantly ease the implementation of templates. I see no such argument.

Type Argument Attributes

"Should a user be required to specify the set of operations that may be used for a template argument of type *type*?" For example:

```
        // The operations =, ==, <, and <=
        // must be defined for an argument type T

template <
                class T {
                        T& operator=(const T&);
                        int operator==(const T&, const T&);
                        int operator<=(const T&, const T&);
                        int operator<(const T&, const T&);
                };
        >
        class vector {
        // ...
        };
```

No. Requiring the user to provide such information decreases the flexibility of the parameterization facility without easing the implementation or increasing the safety of the facility.

Consider `vector<T>`. To provide a sort operation one must require that type `T` has some order relation. This is not the case for all types. If the set of operations on `T` must be specified in the declaration of `vector` one would have to have two vector types: one for objects of types with an ordering relation and another for types without one. If the set of operations on `T` need not be specified in the declaration of `vector` one can have a single vector type. Naturally, one still cannot sort a vector of objects of a type `glob` that does not have an order relation. If that is tried, the generated sort function `vector<glob>::sort()` would be rejected by the compiler.

It has been argued that it is easier to read and understand parameterized types when the full set of operations on a type parameter is specified. I see two problems with this: such lists list would often be long enough to be de facto unreadable and a higher number of templates would needed for many applications.

Should experience show a need for specifying the operations on a parameterized type then such a facility can be easily and compatibly added later.

Source Code

There might be a more fundamental reason for requiring that the operations performed on a template argument of type *type* should be listed in the template declaration. The implementation technique outlined here achieves near optimal run-time characteristics by requiring the complete source code of a template to be available to the compiler when processing a use of the template. In some contexts, this is considered a deficiency and an implementation of templates that requires only the object code for functions implementing the function templates would be preferable.

At first glance it would appear that requiring the full set of operations on a template argument to be specified would make it significantly easier to produce such an implementation. In this case, a function template would be implemented by code using calls through vectors of function pointers to perform operations on template arguments of type *type*. The specification of the set of operations for a *type* argument would provide the definition for such vectors. Such an implementation would trade run-time for compile and link time, but would be semantically equivalent to the implementation scheme presented here.

Could an implementation along these lines be provided without requiring the user to list the set of operations needed for each function template argument of type *type*? I think so. Given a function template, the compiler can create a vector layout for the required set of operations without the help of a user. Given the full set of function definitions for the members of a class, the compiler can again create a vector layout for the required set of operations without the help of a user. If the compile and link environment cannot provide such a list a less optimized scheme where each member function has its own vector of operations can be used.

It thus appears that both implementation styles can be used even in the absence of template argument attribute lists so that we need not require them to preserve the implementers' freedom of action. It might be noticed that a virtual function table is in many ways similar to a vector of operations for a template so that the benefits of the vector of operations approach can often be achieved by a coding style relying on virtual functions rather than the expansion of function templates. Class `pvector` presented in the section below on Type Equivalence is an example of this.

Type Instantiation

"Should a user be required to explicitly declare what versions of a template can be used in a program?" For example, should one require the use of an operation like Ada's `new`? No. Such a requirement would increase the size of the program text and decrease the flexibility of the template facility without yielding any benefits to the programmer or the implementer.

Type Variables

"Should it be possible for a user to declare variables of type *type*?" For example:

```
type t = int;

void f(type t)
{
        switch (t) {
        case int:
                ...
        case char*:
                ...
        case complex:
                ...
        default:
                ...
        }
}
```

Such a facility would be useful in many contexts, but does not appear suitable for C++. In particular, it is not possible to assign integer values to represent constants of type *type* such as `int`, `line_module*`, `double(*)(complex*,int)`, and `vector<complex>` while maintaining the current style of separate compilation. Since the C++ type system is open such assignment of values in general requires an unbounded number of bits to represent a type. In practice, even simple cases require lots of bits (the current cfront scheme for encoding function types in character strings regularly uses dozens of characters) or some system of hashing involving a database of types. Furthermore, the introduction of such variables would require an order of magnitude greater changes to the C++ language and its implementations than the scheme (without type variables) described here.

Type Inquiries

It would be possible to enable a programmer to inquire about properties of a template argument of type *type*. This would allow the programmer to write code that depends on specific properties of the actual types used.

An Inquiry Operator

Consider providing a print function for a vector type that sorts the elements before printing if and only if sorting is possible. A facility for inquiring if a certain operation, such as <, can be performed on objects of a given type can be provided. For example:

```
template<class T> void vector<T>::print()
{
        if (?T::operator<) sort();// if (T has a <) sort_this_vector
        for (int i=0; i<sz; i++) { ... }
}
```

Because the < operation is defined for *ints*, printing of a `vector<int>` gives rise to an expansion:

```
void __PTvector_int::print()
{
        sort();             // that is, this->sort()
        for (int i=0; i<sz; i++) { ... }
}
```

On the other hand, printing a `vector<glob>` where the < operation is not defined for `globs` gives rise to an expansion:

```
void __PTvector_glob::print()
{
        for (int i=0; i<sz; i++) { ... }
}
```

Tests on expressions of the form *?typ::oper* ("does type *typ* have an operation *oper*?") must be evaluated at compile time and can be part of constant expressions.

It would probably be wise *not* to include such a type inquiry feature in the initial experimental implementation but to wait and see what properties (if any) programmers would find useful. Potentially every aspect of a type known to the compiler can be made available to the programmer; `sizeof` is a most rudimentary version of this kind of facility.

The absence of a type inquiry facility will be compensated for by the ability to define a function for a particular set of template arguments, thus overriding the generation of the "standard" version from the template. Furthermore, it can sometimes be preferable to define separate templates to represent the different concepts. For example, one might have both a `vector<T>` class and a `sorted_vector<T>` class derived from it.

The `typeof` Operator

Writing code where the control flow depends of the properties of a type parameter doesn't appear to be necessary, but defining variables of types dependent on type parameters does. Given a template argument of type *type*, `T`, one can express a variety of derived types using the declarator syntax; for example, `T*`, `T&`, `T[10]`, `T(*)(T,T)`. One can also express types obtained by template expansion such as `vector<T>`. However, this does not conveniently express all types one might like. In particular, the ways of expressing types that depend on two or more template arguments are weak. To compensate, one might introduce a typeof operator that yields the type of its argument. For example:

```
template<class X, class Y> void f(X x, Y y)
{
        typeof(x*y) temp = x*y;
        // ...
}
```

It would probably be wise *not* to introduce a typeof operator before gaining more experience. The uses of typeof appears to be quite limited and the scope for misuses large. In particular, typeof appears more suited for the writing of macros (which templates are designed to replace in many contexts) than for templates and heavy use of typeof will reduce the compilers ability to pinpoint type errors.

More about Implementation

So how can we generate the proper code for definitions of operations on a template for a given set of arguments? Assume that we know that versions of vector's subscripting operation

```
template<class T> vector<T>::operator[](int) { ... }
```

are needed for T==int and T==complex. How can we create the proper expansions (as presented above)?

We might have a compiler option, -X, for creating such expansions. Assuming that the definitions for vector's member functions resides in a file called vector.c, one might call the compiler like this:

```
CC -X "vector<int>" vector.c
CC -X "vector<complex>" vector.c
```

and have the appropriate .o files created. This would create not only the required subscript operator functions but also functions for any other vector operation that has its definition stored in vector.h. The strategy for splitting a program into separately compiled parts is in the hands of the programmer. Where a finer granularity is required of .o files for a library, the programmer can handle it using standard C library techniques.

Note that an expansion using the template expansion option, -X, may give rise to a program that uses an instance of a template that has not already been used in the program. This implies that another stage of "missing template implementation detection" is required after each expansion. Expansion is really a recursive activity. The depth of this recursion will typically be 1, though. It will be necessary to have a mechanism protecting against recursive expansion. For example:

```
template<class T> void f(T a) { T* p; ... f(p); }
```

Naturally, one would try to ensure that CC -X is used to generate .o files only for definitions of templates when

[1] a new template was used, or

[2] a new set of template arguments was used, or

[3] the declaration of a template was changed.

I imagine that after a short startup period all the necessary `.o` files for templates for a program/project will reside in a library and not interfere with the compilation process. When a program/project reaches this state the compilation overhead incurred by using templates becomes negligible.

Tools for Ensuring Consistent Linking

Consider having the tools described above:

[1] a C++ compiler handling the expansion of class templates into class declarations, and

[2] a `-X` option on this compiler to handle the expansion of function templates into function definitions.

One could then compile a C++ program using templates. A little manual intervention would be needed to get a complete program to link and load.

What additional tools would be needed to

[1] guarantee consistent and complete expansion and linking?

[2] make programming reasonably convenient?

I conjecture that [1] is perfectly feasible, but non-trivial, where portability across operating systems, compile and link time efficiency, and flexibility are all required. I also conjecture that very little is needed to achieve [2]. Experience using such a system is clearly needed, but it might well be sufficient to modify a tool with access to the complete compiled program, such as `munch` or the linker itself, to produce

[1] a list of function definitions required, or

[2] a list of files for which `CC -X` needs to be run (assuming some correspondence between type names and file names), or

[3] a make script for running `CC -X` for an appropriate set of files.

It would also be important to ensure that `CC` produces readable error messages when an operation is applied to a particular template argument of type *type* for which it is not defined. For example:

```
"foo.c", line 144: error: operator<= applied to glob in vector<glob>::sort()
```

This discussion of how one might provide a minimal and portable mechanism supporting templates in C++ should not be taken as an indication that such a mechanism provides the ideal programming environment. On the contrary, it is exactly a *minimal* facility. Much better facilities can be built (think of a smart `make`, an incremental compiler, a Smalltalk-like browser, etc.), However, a minimal facility *must* exist to ensure portability of C++ programs between all implementations since there is no hope that a single maximal programming environment will ever be agreed on and implemented on every system supporting C++.

Function Templates

In addition to providing class templates, it is necessary to provide function templates. Consider providing a general `sort` function:

```
template<class T> void sort(vector<T>);
```

Given a vector `v`, one might call such a function like this:

```
sort(v);
```

The compiler can deduce the type of the sort function from the type of the vector. For example, had `v` been declared

```
vector<int> v(10);
```

the sort function `sort<int>` would have been required. On the other hand had the declaration of `v` been

```
vector<double> v(2000);
```

the sort function `sort<double>` would have been used.

Overloading

Declaring a function template is simply a way of declaring a whole bundle of overloaded functions at one time. This implies that we can use functions with arguments that can be distinguished by the overloaded function resolution mechanism only. The following function cannot be used because it takes no argument:

```
template<class T> T* create() { return (T*) malloc(sizeof(T)); }
```

The C++ syntax could be extended to cope with this by allowing the full generality of the *name<type>* notation so that template arguments could be supplied explicitly in a call:

```
int* pi = create<int>();  // create_int()
char* pc = create<char>();// create_char()
```

Unless programmers define templates sensibly this form of resolution can become quite cryptic:

```
template<class X, class Y> f(Y,X);  // template argument order differs
                                    // from function argument order
 ...
f<char*,int>(1,"asdf");
```

I think it would be wise not to include any explicit resolution method in an initial implementation. I suspect that the implicit resolution provided by the overloaded function resolution rules are sufficient – and more elegant – in almost all cases and it is not obvious that a mechanism for explicit overloading is worth the added complexity.

Allowing explicit resolution would imply that a C++ compiler should treat function template names differently from other names and similarly to the way keywords and class names are treated. For example, without special rules for template names the last expression above would be parsed as two comparisons and a parenthesized comma expression:

```
(g<123)>(vv,10);
```

A Problem

Consider writing a function `apply()` that applies another function to all the elements of a vector. A traditional first cut would look something like this:

```
template<class T> void apply(vector<T>& v, T& (*g)(T&))
{
        for (int i = 0; i<v.size(); i++) v[i] = (*g)(v[i]);
}
```

This follows the C style of using a pointer to function. Potential problems with this are

[1] efficiency, because there can be no inline expansion of the applied function, and

[2] generality, because standard operations of built-in types such as - and ~ for `int`s cannot be applied.

Naturally, these are not problems to all people. However, an ideal template mechanism will provide solutions.

A Solution

One might consider the function to be applied by `apply()` a template argument rather than a function argument:

```
template<class T, T& (*g)(T&)> void apply(vector<T>& v)
{
        for (int i = 0; i<v.size(); i++) v[i] = (*g)(v[i]);
}
```

To call `apply()` one must specify the function to be applied. Since this version of `apply()` takes only a single `vector` argument the syntax for disambiguating an overloaded function call using `<...>` must be used:

```
class X { ... };

vector<X> v2(200);

inline void hh(X&) { ... };
void gg(X&); // not inline

apply<X,hh>(v2);
apply<X,gg>(v2);
```

Clearly, the `X` is redundant and not elegant. Since in principle each such call of `apply()` results in writing a new function `apply()` inlining can be applied where sufficient information is available. Consequently, one would expect a C++ compiler to inline `hh()` in the first call in the example above and generate a standard function call of `gg()`. The fact that function pointers and not functions are passed in C++ is at most a minor annoyance for the compiler writer.

Operators for built-in types can be considered inline functions in this context:

```
vector<int> v(100);
apply< int, &int::operator-- >(v);
```

However, as for the explicit resolution scheme itself, it remains to be seen if this degree of sophistication and complexity is actually needed.

Syntax Issues

Consider the declarations:

```
template<class T> class vector { ... };
template<class T> T* index<class T>(vector<T>,int);
```

[1] Why use the `template` keyword?

[2] Why use `<...>` brackets and not parentheses?

[3] Why use the `class` keyword?

[4] What is the scope of a template argument?

The `template` keyword

If a keyword is to be used `template` seems to be a reasonable choice, but it is actually not necessary to introduce a new keyword at all. For class templates, the alternative syntax seems more elegant at first glance:

```
class vector<class T> {          // possible alternative class syntax
        ...
};
```

Here the template arguments are placed after the template name in exactly the way they are in the use of a class template:

```
vector<int> vi(200);
vector<char*> vpc(400);
```

The function syntax at first glance also looks nicer without the extra keyword:

```
T& index<class T>(vector<T> v, int i) { ... }
```

There is typically no parallel in the usage, though, since function template arguments are not usually specified explicitly:

```
int i = index(vi,10);
char* p = index(vpc,29);
```

However, there appears to be nagging problems with this "simpler" syntax. It is too clever. It is relatively hard to spot a template declaration in a program because the template arguments are deeply embedded in the syntax of functions and classes and the parsing of some function templates is a minor nightmare. It is possible to write a C++ parser that handles function template declarations where a template argument is used before it is defined, as in `index()` above. I know, because I wrote one, but it is not easy nor does the problem appear amenable to traditional parsing techniques. In retrospect, I think that not using a keyword and not requiring a template argument to be declared before it is used would result in a set of problems similar to those arising from the clever and convoluted C and C++ declarator syntax.

<...> vs (...)

But why use brackets instead of parentheses? As mentioned before, parentheses already have many uses in C++. A syntactic clue (the `<...>` brackets) can be useful for reminding the user about the different nature of the type parameters (they are evaluated at compile time). Furthermore, the use of parentheses could lead to pretty obscure code:

```
template(int sz = 20) class buffer {
        buffer(int i = 10);
        // ...
};

buffer b1(100)(200);
buffer b2(100);          // b2(100)(10) or b2(20)(100)?
buffer b3;          // legal?
```

These problems would become a serious practical concern if the notation for explicit disambiguation of overloaded function calls were adopted. The chosen alternative seems much cleaner:

```
template<int sz = 20> class buffer {
        buffer(sz)(int i = 10);
        // ...
};

buffer b1<100>(200);
buffer b2<100>;          // b2<100>(10)
buffer b3;          // b3<20>(10)
buffer b4(100);          // b4<20>(100)
```

The `class` keyword

Unfortunately, the ideal word for introducing the name of a parameter of type *type*, that is, `type` cannot be used; `type` appears as an identifier in too many programs. Why use the `class` keyword then? Why not? Classes are already types to the extent that the built-in types can be considered second class citizens in some contexts (you cannot derive a class from a built in type, you cannot take the address of an operation on a built-in type, etc.). What is done here is simply to use `class` in a slightly more general form than is done elsewhere.

Scope of Template Argument Names

The scope of a template argument name is the template declaration and the template name obeys the usual scope rules:

```
const int T;

template<class T>   // hides the const int T
class vector {
      int sz;
      T* v;
public:
      // ...
};

int T2 = T;         // here const int T is visible again
```

Template declarations may not be declaration lists:

```
template<class T> f(T*), g(T);   // error: two declarations
```

This restriction is made to avoid users making unwarranted assumptions about relations between the template arguments in the different templates.

Templates and Typedef

The template concept is easily extended to cover all types[1]. For example:

```
template<class T, int i> typedef T array[i];
 ...
array<int,10> v;    // array of 10 ints
```

This allows great freedom in defining type names. The `typedef` keyword is necessary because

```
template<class T, int i> T array[i];
```

Would define a family of arrays (all called `array`) and not a family of array type.

Consequently, only class, function, and typedef templates will be implemented.

Type Equivalence

Consider:

```
template<class T, int i> class X {
      T vec[i];
      // ...
};

array<int,10> x;
array<int,10> y;
array<int,11> z;
```

Here, x and y is of the same type, but z is of the different type. Since the template arguments used in the declarations of x and y are identical they refer to the same class. Naturally, only a single class declaration is generated by a C generating C++ compiler. On the other hand, the template arguments used in the declaration of z differs and gives rise to a different class.

Different template arguments give rise to different classes even if the argument is used in a way that does not affect the type of the generated class:

```
template<class T, int i> class Y {
public:
      foo() { int buf[i]; ... }
};

Y<int,10> xx;
Y<int,10> yy;
Y<int,11> zz;
```

Template arguments must be types, constants, or integer expression that can be evaluated at compile time.

Derivation and Templates

Among other things, derivation (inheritance) ensures code sharing among different types (the code for a non-virtual base class function is shared among its derived classes). Different instances of a template do not share code unless some clever compilation strategy has been employed. I see no hope for having such cleverness available soon. So, can derivation be used to reduce the problem[2] of code replicated because templates are used? This would involve deriving a template from an ordinary class. For example:

```
template<class T> class vector {        // general vector type
      T* v;
      int sz;
public:
      vector(int);
      T& elem(int i) { return v[i]; }
      T& operator[](int i);
      // ...
};

template<class T>
class pvector : vector<void*> {        // build all vector of pointers
                                  // based on vector<void*>
public:
      pvector(int i) : (i) {}
      T*& elem(int i) { return (T*&) vector<void*>::elem(i); }
      T*& operator[](int i) { return (T*&) vector<void*>::operator[](i); }
      // ...
};

pvector<int*> pivec(100);
pvector<complex*> icmpvec(200);
pvector<char*> pcvec(300);
```

The implementations of the three vector of pointer classes will be completely shared. They are all implemented exclusively through derivation and inline expansion relying on the implementation of vector<void*>. The vector<void*> implementation is a good candidate for a standard library.

I conjecture that many class templates will in fact be derived from another template. For example:

```
template<class T> class D : B<T> {
      ...
};
```

This also ensures a degree of code sharing.

Members and Friends

Here are some more details:

Member Functions

A member function of a class template is implicitly a template with the template arguments of its class. Consider:

```
template<class T> class C {
        T p;
        T m1() { T a = p; p++; return a; }
};

C<int> c1;
C<char*> c2;

int i = c1.m1();    // int C<int>::m1() { int a = p; p++; return a; }

char* s = c2.m1();  // char* C<char*>::m1() { char* a = p; p++; return a; }
```

These two calls of `m1()` gives rise to two expansions of the definition of `m1()`.

Naturally a member template may also be declared:

```
template<class T> class C {
        template<class TT> void m(TT*,T*);
};
```

This case will be discussed below. However, explicit use of class template arguments in member function names is unnecessary and illegal:

```
template<class T> class C {
        T m<T>();               // error
};

template<class T> C<T>::m<T>() { ... }       // error

template<class T> C<T>::m() { ... }          // correct
```

This also applies to constructors:

```
template<class T> class C {
        C();                // correct, a constructor
        C<T>(int);          // error constructor
};

template<class T> C<T>::C() { ... }     // correct
```

To avoid confusion it is not legal to define a template as a member with the same template argument name as was used for the class template:

```
template<class T> class C {
      template<class T> T m(T*);                    // error
};
```

Friend Functions

A friend function differs from other functions only in its access to class members. In particular, a friend of a class template is not implicitly a template. Consider:

```
template<class T> class C {
      friend f1(T a);
      template<class TT> friend f2(TT a);
};
```

The definitions of `f1()` and `f2()` are legal, but clearly not equivalent.

The `friend` declaration of `f1(T)` specifies that for all types `T`, `f1<T>` is a friend of `C<T>`. For example, `f1<int>` is a friend of `C<int>`. However, `f1<int>` is not a friend of `C<double>`. The definition of `f1()` would probably look something like this:

```
template<class TT> f1(TT a) { ... };
```

The friend `f1()` need not be a template, but if it isn't the programmer might have a tedious time constructing the necessary set of overloaded functions "by hand."

The declaration of `f2()` specifies that for all types `T` and `TT`, `f2<TT>` is a friend of `C<T>`. For example `f2<int>` is a friend of `C<double>`.

Note that a friend function of a parameterized class need not itself be parameterized:

```
template<class T> class C {
      static int i;
      friend f() { i++; }
};
```

Static Members

Each version of a class template has its own copy of the static members of the class:

```
template<class T> class C { static T a; static int b; ... };

C<int> xx;
C<double> yy;
```

This implies allocation of the static variables:

```
static int C<int>::a;
static int C<int>::b;

static double C<double>::a;
static int C<double>::b;
```

Similarly, each version of a parameterized function has its own copy of static local variables:

```
template<class T> f() { static T a; static int b; ... };
```

Friend Classes

Friend classes can (as usual) be declared as a shorthand for declaring all functions friends:

```
template<class T> class C {
        friend template<class TT> class X;      // all X<TT>s
        friend class Y<T>;              // only Y<T>
        friend class Z<int>;                    // only Z<int>
};
```

Examples of Templates

Here are some more examples of potentially useful templates. Versions of many of the templates used as examples in this paper have been created using macros and actually used in real programs. "Faking" templates using macros have been a major design technique for the template facilities. In this way the language facilities could be designed in parallel with the key examples and techniques they were to support.

An associative array:

```
template<class E, class I> class Map {
        // arrays of Es indexed by Is
        // ...
        E& operator[](I);
};
```

A "record" stream; the usual stream of characters is a special case:

```
template<class R> class ostream {
        // ...
        ostream<R>& operator<<(R&);     // output an R
};
```

An array for mapping information from files into primary memory:

```
template<class T, int bsz> class huge {
        T in_core_buf[bsz];
        // ...
        T& operator[](int i);
        seek(long);
        // ...
```

A linked list class:

```
template<class T> class List { ... };
```

A queue tail template for sending messages of various types:

```
template<class T> class mtail : public qtail {
        // ...
        void send(T arg)
        {
                // bundle ''arg'' into a new message buffer
                // and put than on the queue
        }
};
```

A counted pointer template (for user-defined automatic memory management):

```
template<class T> class CP {
        // ...
public:
        CP();
        CP(T);
        CP(CP<T>&);
        // ...
};
```

Conclusions

A general form of parameterized types can be cleanly integrated into C++. It will be easy to use and easy to document. The implementation can be efficient in both run-time and space. It can be implemented portably and efficiently (in terms of compiler and link time) provided some responsibility for generating the complete set of definitions of function templates is placed on the programmer. This implementation can be refined, but probably not without loss of either portability or efficiency. The required compiler modifications are manageable. In particular, cfront can be modified to cope with templates. Compatibility with C is maintained.

Caveat

The key thing to get right for a C++ template facility is assuring that basic parameterized classes are implemented in an easy to use and efficient way for the relatively simple key examples. The compilation system *must* be efficient and portable at least for these examples. The most reasonable approach to building a template system for C++ would be to achieve this first, make the inevitable changes in concepts based on that experience, and proceed with more advanced features *only* as far as they makes sense *then*.

Footnotes

1. This section has been changed since the USENIX C++ conference proceedings version of this paper based on comments by George Gonthier.

2. If that really is a problem: memory is cheap, etc. I think it is a problem and will remain so for the foreseeable future. People's expectations of computers have consistently outstripped even the astounding growth in hardware performance.

7 Template Instantiation – Overview

Template Instantiation in C++ Release 3.0.1 - Overview

NOTE

This chapter is taken directly from a paper by Glen McCluskey and Robert B. Murray.

Introduction

This chapter describes how the USL C++ compiler version 3.0.1 handles automatic template instantiation and briefly reviews alternate strategies. The chapter does not cover practical usage of the instantiation system; this topic is discussed in *Template Instantiation in C++ Release 3.0.1 - User Guide,* which follows.

The template environment is an *implementation* of the template language feature described in *The Annotated C++ Reference Manual* (M.A. Ellis and B. Stroustrup, Addison-Wesley, 1990). Please note that, unlike the language itself, implementations are not subject to formal standardization and are therefore subject to change.

Templates and Instantiation

A *template* is a skeleton for defining a set of types or functions. Each type or function of the set is created by combining the template with a set of arguments that are themselves types or values. This process is known as *instantiation.*

For example, consider a template such as the following:

```
template <class T> class List {
        T* items;
        int count;
public:
        void additem(T);
        /* ... */
};
```

This declares a template called `List`, with two data members `items` and `count`, and one member function `additem`. If one were to use this template in an application by saying

```
main()
{
        List<double> li;

        li.additem(12.34);
}
```

then a particular combination of the template `List` and the argument `double` would be instantiated, with two data members and one publicly-accessible member function `List<double>::additem(double)`.

The instantiation problem is one of creating compiled files (object files) containing the instantiations needed by an application. These files should be minimal in size; only members of the template used in the application should be instantiated. The user may have provided a special case for a template member or a complete template class, and this *specialization* should override any automatic instantiation procedure.

Definitions of Terms

We will use the following terms in this chapter (a complete glossary is given at the end).

The *template declaration file* of a template is the file that contains the template declaration (for example `List.h` might contain the declarations for `List`). These declarations must be present in any file that refers to the template, that is, `#included`.

The *template definition file* of a template is the file that contains the definitions of the template members (for class templates), or the definition of a function template (`List.c` might contain the definitions for `List`). These definitions are required to instantiate a template, but not to refer to it.

The *argument declaration file* of a named type is the file that contains the declaration of that type (`String.h` might contain the declarations for `String`). The argument declarations of all the type arguments are needed to instantiate a template.

To instantiate a template, you need the template declaration file, the template definition file, and the argument declaration files for each template type argument. For example, to instantiate `List<String>`, you might need `List.h` (template declaration file for `List`), `List.c` (template definition file for `List`), and `String.h` (argument declaration file for `String`).[1]

Overall Instantiation Strategies

The basic idea of template instantiation is that the linker figures out which template functions you used and for which argument types, finds the template function definitions, and generates the functions needed. This will work completely automatically provided that a class or template `C` is declared in a file `f.h` and its non-inline functions are defined in `f.c`. The following sections will describe template instantiation in detail, explain some of the design choices made, and show how the default conventions can be overridden.

The instantiation schemes that we have seen so far fall into one of three families. Two of these use a *repository*; this is conceptually an archive of template instantiations, although it need not be implemented as a UNIX™ system archive.

Instantiate as You Go

Every compile is done with reference to a repository of existing template instantiations. When a reference to a template is compiled, the repository is checked to see if a valid instantiation for that template exists. If it does not, the template is instantiated (in a separate object file) and the result put into the repository.

The advantage of these schemes is that the declarations of both the templates and the argument types are available (since the file that referenced the template must have had them available). This avoids problems with having to "go back later" and find the template and argument declaration files.

If the general version of a template does not compile, but a special case version (specialization) will be presented at link time, these schemes will still attempt to compile the general version and produce error messages. The user would have to know enough to ignore these messages, if and only if a specialization is going to be presented at link time.

In addition, these schemes place severe constraints on makefiles. If a template declaration or definition, or an argument declaration, is changed, the makefiles must be smart enough to remove the changed instantiations from the repository *before any other source files are compiled to object files.* In general this requires adding an extra dependency to every makefile rule. If the makefile has a bug, the application may appear to compile but would not link until the files that referred to the missing instantiations were recompiled (even though those files had not changed). Or worse, the application may fail at runtime because of an incorrect instantiation being used. This behavior is just too mysterious and error prone.

Manual Instantiation

With a manual instantiation scheme, the user is responsible for writing one or more files that specify exactly which templates are to be instantiated. Or the user might specify `#pragma` directives to achieve the same end. This may seem to be the easiest to implement; however, there is a snag. If a template `Stack<T>` uses `List<T>` in its implementation, how does the instantiation of `Stack<T>` cause `List<T>` to get instantiated?

One way is to force the user to ask for the instantiation of `List<T>`. This violates encapsulation: the user should not have to know that `Stack<T>` uses `List<T>`.

Alternatively, the system could be smart enough to figure out that `Stack<T>` uses `List<T>`, and to instantiate it if and only if `List<T>` is not instantiated anywhere else. However, if the system is smart enough to do this, it should also be smart enough to figure out which templates the *user's* code referred to! In this case it ought to be able to do instantiation automatically.

The point is that *a manual instantiation scheme that does not violate encapsulation must be smart enough to do automatic instantiation.* There is no "middle ground". We have therefore abandoned totally manual approaches.

Link–Directed Instantiation

Every compile is done with a repository (or path of repositories) of existing template instantiations. Objects from this repository are linked when the linker is called. If the link fails because of unresolved references, nm is run on the output and a list of required template members is generated. These templates are then instantiated, added to the repository, and the link phase repeated until all needed templates have been instantiated.

Why a repository? Instantiation of template functions for a large program can be a relatively slow process. It is therefore important that a function is not reinstantiated unnecessarily. The repository ensures that a template function is instantiated the first time a program using it is linked and after each change to the program that affects the definition of a template function - and *not* simply at each compilation or linking. This implies that compiling a program for the first time and after a major change can be relatively slow but that a typical compile and link step is hardly affected by template instantiation overhead.

These schemes have important advantages:

- Only the template members that are used are instantiated. If a special case instantiation is provided at link time, no attempt is made to instantiate the corresponding general version.
- Since the instantiation process takes place at link time, the repository only has to be updated by link time, not by the compile time of any source file that uses a template. This avoids complicating the makefiles.

The disadvantages of link-directed instantiation are:

- There must be a well-defined and easily understood set of rules that the instantiator uses to find the template declaration, template definition, and argument type declaration files.
- References to templates that will not instantiate are not discovered until link time. We do not believe this is serious, especially since any apparent reference to a general template member may be a reference to a specialization provided at link time. Because of this, checking that a template is not bogus at the point of reference is not feasible.
- The number of iterations needed to initially populate the repository can be large. If we examine the call graph of the final program, give every call of a template member or function template cost 1, and every other call cost 0, then the number of iterations is potentially the diameter of the resulting graph. (This is the longest of the shortest paths between every two nodes in the graph.) We do not have a good handle on how many iterations this will be, though observations from existing programs suggest an upper limit of 3-4 iterations in practice. However, to reduce the overhead, we will emulate some of the linker functionality in a "pre-linker" to avoid the overhead of multiple links. This tool reads the symbol tables of the objects and archives, determining which unresolved references would draw in which files. It does not do any relocation. This allows us to only do one link at the end when we know that all the required instantiations are available.

The remainder of this chapter describes our instantiation scheme.

Executive Summary

This section gives a high-level overview of the instantiation process. Later sections will go into more detail.

1. For all compilations, there is a *current repository* into which instantiations are stored. The instantiation system modifies the repository but does not clean up obsolete files within it.
2. When a C++ file that references templates is compiled, the references are compiled normally into external unresolved symbols, but nothing is instantiated. (Exception: a specialization of a general-purpose template is compiled in the object file that it appears in, and is the same as a normal class declaration and implementation).
3. Every class, union, struct, or enum that is declared is logged in a *name mapping file* in the current repository. The entry includes the type name and the basename (not full pathname) of the file in which the declaration appears; the basename-only rule is used to simplify moving applications from one directory to another.
4. Every template that is declared is also logged in the name mapping file. Definitions of members of class templates are *ignored;* there is no use for individual member information.
5. At link time, a *pre-linker* determines whether a link would succeed, that is, it looks at all the files and archives, and the current repository, to determine whether there are any referenced template symbols that are unresolved. Header caches are used to make sure that any instantiations in the repository that are out of date are not used. If there are no unresolved symbols, we do a link, and are done.
6. If there are unresolved symbols, the instantiator builds a list of class templates and function templates that must be instantiated. For each template, the name mapping file is consulted to find the template declaration file, and the argument declaration files for all of the template arguments.

   Unless explicitly specified by the user (see the section below on overriding name mapping files), the template definition file is assumed to be the file with the same name as the corresponding template declaration file, except that it has a `.c` suffix.
7. When templates are used, a `-I` path (the same one used for compiling) must be passed to the pre-linker. This -I path is used to find the template declaration file, the template definition file, and the argument declaration files. If any of these files are not found, the link fails with an appropriate diagnostic.
8. The template declaration file, the template definition file, and the argument declaration files are used to build a temporary *instantiation file.* The C++ compiler is then called to instantiate the template. The compile is done in *directed mode;* that is, the compiler is directed to only generate code for a specified list of symbols. If this is a class template, only the members that were needed are instantiated. The resulting object file is added to the repository.
9. Steps 6–8 are repeated for every template class or function that needs to be instantiated.
10. When all the instantiations have been done, the pre-linker is called again. Since some of the new instantiations may refer to new symbols, this process may iterate (back to step 5).

11. The result of the pre-linker is a set of object files containing the instantiations. These objects are passed to the actual link step.

The rest of this paper describes the process in detail, including the ways that users can exercise finer control over the instantiation process.

Detailed Description of the Instantiation Process

Repositories

A *repository* is a UNIX™ directory used to store information about instantiations and types. It should not be confused with an archive library of object files. A repository pathname can be specified by the user at compile or link time. The default repository is a subdirectory of the current directory and is automatically created (but not automatically cleaned up).

The repository contains several kinds of information:

- Name mapping files that map a template or named type to the name of the file that declares it. By default, only the basename of the file (after stripping `-I` prefixes), not its full pathname, is stored.
- Object files that contain template instantiations.
- Checksum files containing a list of needed members for each instantiation.

Compile-Time Actions

The C++ compiler maintains a name mapping file, which records the name of the file in which a class, struct, union, or enum type is declared. The extraction of type information is done by the C++ compiler after preprocessing. The compiler relies on `#line` entries in preprocessor output to determine what source file is being translated. For all class, enum, and template types, the compiler notes the basename of the file currently being translated. Typedefs, except for typedefs of anonymous structs, are ignored because they are expanded to the underlying type, which is used to encode external names. Local and unnamed types are ignored, and only the outermost type in a nested type is used.

For each type extracted, the name of the type and the basename of the file where it is declared is recorded in the name mapping files, together with the basename of the application file being compiled:

```
@dec Vector appl
"Vector.h"
@dec A app2
<A.h>

@dec B app2
<A.h>
@dec C
"C.h"
```

The @dec keyword indicates a declaration. This file shows that template Vector is declared in Vector.h, class A is declared in A.h, and class B is also declared in A.h. The #include quote type is recorded with the file to preserve preprocessor semantics.

The header basename is computed by comparing the pathname reported by the preprocessor against all the -I directives and deleting any prefix that matches. Sometimes this will result in a name such as sys/stat.h.

Two application files app1 and app2 are used in this example. Application file names are recorded to support the case where two applications share one repository. If no application basename is given, then the @dec entry is a default one that is used as a last resort; the fourth entry is an example. The type lookup algorithm is described in section 6.3.

For function templates, the type name is the function name without arguments. For example:

```
@dec f app3
"f.h"
```

for the function f(char*) that came from:

```
template <class T> void f(T t);
```

Because arguments are not recorded, map file entries for function templates contain the union of all files where the template was declared.

The name mapping files in the repository are not updated if the compile fails. If the resulting mapping files have multiple entries for the same type and application basenames, as in:

```
@dec A app1
<A.h>
@dec A app1
<B.h>
```

then an error is given at pre-link time, if the type is needed (lazy type lookup).

Also, if a header file previously existed in some of the entries in the default name mapping file, all the entries for that header are deleted before updating with new information. When a source file is compiled a list is made of all headers it contains. Each entry in the map file that has one of the same headers, and that contains a matching application name, is deleted before new entries are added. This tends to reduce the buildup of garbage.

User Overriding of Name Mapping Files

The compiler automatically generates its own name mapping files. However, users can override these name mapping files for special cases by writing their own. For instance, suppose that use of class A requires that both A.h and B.h be included, in that order, for the declaration to compile. Then the user-specified name mapping file must read:

```
@dec A
<A.h>
<B.h>
```

Users can also override the rule that the name of the template definition file is the name of the template declaration file, except with a `.c` suffix, by placing a `@def` directive in the name mapping file:

```
@dec List
"List.h"
@def List
"List_impls.c"
```

Here template `List` is declared in `List.h`, but the definitions of its members can be found in `List_impls.c`. The compiler never generates `@def` directives automatically.

User-specified type information is given in `nmapXXX` files (such as `nmap037`), while automatically generated information is in `defmap` ones. `nmapXXX` files are considered in alphabetical order.

Auto-generated name mapping files have only the basename of the header file. User-specified ones may have arbitrary pathnames, though the standard `-I` convention is followed and recommended for ease of moving application code.

User-specified map files have precedence over the auto-generated one, if the application basenames match at type lookup time. The exact order of type lookup is:

- Try to find matching type/basename in user-specified files.
- Look for a default `@dec` entry in user-specified files.
- Try to find matching type/basename in auto-generated map file.
- Look for a default `@dec` in auto-generated map file.
- If not a template type, generate a forward declaration.
- If a template type `T`, assume it is declared in `T.h` and defined in `T.c`. Issue a warning.

Link-Time Actions

At link time, the name mapping file must be up-to-date and available to guide instantiation. Before linking, the compiler needs to determine what, if any, instantiations are necessary, and generate them as object files to be fed into the actual link. If the repository is empty or does not exist, no pre-linking is done, and the non-template case therefore incurs no extra processing time.

The first step in the process is to determine what external symbols are unresolved in the application. Standard UNIX™ linking calls for object files to be unconditionally linked, while object files in an archive are linked only if symbols from them are needed. It is therefore not enough to scan all objects and archives looking for unresolved symbols, since that would result in instantiations being done for symbols that are never linked. One solution to the problem is to actually link the program and see what symbols show up as undefined. This is expensive.

So, instead of linking, we simulate the link, by running `nm` on all objects and archives, and then performing the symbol table actions such as would be done in a real link. This approach is much faster than linking, because only the symbol tables of objects and archives must be read; no relocation is done.

Partitioning Symbols and Granularity

The output of the process so far is a set of symbols that are unresolved and for which we must provide instantiations. We screen the set to eliminate non-template symbols, which are assumed to be defined somewhere else. Function templates are encoded just like C++ functions, and so are considered for instantiation only if found in the map files.

Given a list of symbols, we pick apart the symbol names, which encode the template name and argument types, and partition the list according to a desired level of granularity.

By default, all needed symbols for a given template class are instantiated into a single object file. Alternatively, one can specify that each member function for a template class be instantiated in its own object file, with all virtual tables and virtual functions for the class being instantiated into a single object file as well.

Instantiating all symbols in a single object file results in much shorter instantiation times, especially if there is extensive template use in an application. By contrast, instantiating each member function in a separate object file makes it easier to build libraries that can be shared, but can easily cause instantiations that involve hundreds of compiles, especially when the repository is populated for the first time.

Creating the Instantiation File

For each partition of the symbols we create the *instantiation file* with an internally generated name. It is a file that includes all the headers necessary to fully define a template class or function. That is, the file will `#include` the template declaration file, then the template definition file, and then the argument declaration files, in the order that the arguments appear from left to right. (Exception: no file is included more than once). For example, given the name mapping file:

```
@dec Vector app4
<Vector.h>
@def Vector app4
<Vector2.c>

@dec A app4
<A.h>
@dec B app4
<A.h>
```

and an external unresolved symbol

```
Vector<B>::f(int,B)
```

we would come up with a file:

```
#include <Vector.h>
#include <Vector2.c>
#include <A.h>
```

If the type is not found in the name mapping files, it is assumed to be an incomplete type used as the base type of a pointer or reference. For example, for the template class `Vector<A*>`, with `A` not previously seen, the instantiation file would be:

```
#include <Vector.h>
#include <Vector2.c>
struct A;
```

Naming the Instantiation File

Object files stored in the repository are the result of instantiations that are done for particular combinations of templates and arguments. Each object file has a checksum file stored with it. Depending on naming conventions used, an object file and its associated file containing the checksum will have names like:

```
Vector__pt__4_i1A.o
Vector__pt__4_i1A.cs
```

or:

```
pt06717175.o
pt06717175.cs
```

for a template class `Vector<int,A>`.

The first case is used when the operating system supports long names, while the latter convention is used for ones that do not; a hash code of the encoded template class name is used.

Dependency Management

When a template definition or declaration file, or an argument declaration file, is changed, the instantiations that used these files become out of date. We must have some way of detecting this case and redoing the instantiation. The alternative of recompiling all such files at each link is too expensive. On the other hand, a naive scheme, such as not recompiling any instantiation file for which an object already exists, is prone to mysterious errors if an instantiation becomes out of date and is not detected.

For each instantiation file there is a set of unresolved symbols that came from the partitioning described above. If there is no object file in the repository for this instantiation file, or if that object file does not define all the symbols that are needed, the instantiation file is recompiled, with the result replacing the old version in the repository.

If, on the other hand, there is an object file that defines all needed symbols, we then have to decide whether it is up to date, that is, whether any of the header files it included when it was made have changed. To detect changes, a header cache scheme is used. The preprocessor is run on the instantiation file to compute a list of all headers upon which the instantiation depends. The list is stored in the repository with the instantiation, and updated as needed when headers change. The instantiation object is out of date if its timestamp is older than any of the headers upon which it depends.

To determine whether the instantiation defines all the needed symbols, a sorted list of symbols (that will be used for directed instantiation) is included in the checksum file.

Directed Instantiation

If the dependency analysis determines that recompilation is necessary, the instantiation file is compiled in directed mode, with user-specified `-I` and `-D` options to name header file directories. The C++ compiler is passed the instantiation file as a normal source file, along with a list of symbols to be instantiated. No code is generated for other symbols; in a typical case the resulting object file will contain a subset of the functions defined for a particular template class.

Growing Instantiation Files

When using class-level granularity (all the needed members of a class template are in a single object file), a situation can arise where a subset of the members is initially instantiated, but a later iteration of the process expands the set of members that are required. In this case, the instantiator will remove the old object file from the repository, and reinstantiate the entire object file, including the members that were in the original, plus the new members that needed to be added.

Actual Linking

After all the instantiation files have been compiled, we are left with a set of objects for them plus all the application objects and archives. Actual linking cannot yet be done, because the instantiations may have created a need for *additional* symbols. To handle such a case, the symbol tables of the object files are extracted and the whole process repeats.

When the pre-linker is satisfied that all the required symbols are present, then the actual link is performed.

Multiple Repositories

To support large projects, the above scheme is extended to handle more than one repository. Team projects often have a central set of standard versions of source files and headers, with the ability for team members to override these versions with local copies of files. The multiple repository scheme is intended to support such usage.

At compile time, only one repository is recognized. At link time, the first repository specified is considered writeable, while all others are read-only. Any default repository is ignored if a repository is explicitly named.

Type lookup in map files follows the algorithm in the section above on user overriding of name mapping files, except that the algorithm is applied in total to each repository left to right until the type is found.

For instantiation object files, the search is also left to right until an object file is found that defines all required symbols and that passes the dependency checks. If the object file is not found, the instantiation is done into the first, that is writeable, repository.

Repository Locking

A repository may be shared by several people in a team of programmers. If several of them simultaneously try to link, and instantiation takes place in the repository, chaos will result. Therefore a locking scheme using standard UNIX™ system calls is implemented, with stub functions provided for custom locking implementations. If a repository is locked other users wait in an idle loop until it is free. Only the first repository (the writeable one) is locked.

Performance

Performance at compile time (updating the map files) is not significantly affected by this scheme. Extracting type information and updating the repository is an efficient operation.

There is substantial cost in determining which template symbols are unresolved. However, since the alternative might be several actual links, this is a reasonable expense.

Binary sizes are optimal, except for virtual functions in a template class; they are always instantiated, because there is no static way to tell if they are used. This is no different from the non-template case.

The biggest performance issue (beyond instantiation) is that of iteration at link time as instantiations create demand for more symbols. The initial scan of an application might determine that `Vector<A>::f` is needed, and when it is instantiated, it requires `Vector<A>::g`, and so on. There is not a completely clean solution to this problem, except to note that once templates and the headers describing template arguments are in a steady state, the repositories will be up to date, so a full-blown instantiation will rarely be necessary.

Limitations of Our Approach

The most obvious limitation is that of type name mapping. The fully automated scheme requires that a type be described in a single header that is self-contained or that includes the other headers that it needs. The user can override the default and specify arbitrary lists of header files for a single type.

This scheme does not handle local types, that is, types defined within a function. The problem is that reestablishing the context at link time for such a type is difficult at best. There is no way to recreate the scoping and other information for the function that the type appeared in.

Finally, our approach does not handle static data defined in template definition files. For example:

```
static int x = 83;
template <class T> void Vector<T>::f() {int y = x;}
template <class T> void Vector<T>::g() {int z = x;}
```

In this example, two template functions wish to share a file static x. Since the functions may be split up at instantiation time, there is no way to handle this other than by making the file static into a global with some internal naming convention.

Other Approaches to Instantiation

Replaying Source Files

A variant to the above approach is replaying source files. That is, at link time determine what application source file uses a particular template symbol. Such a file must by definition have all the required type information available to it except for the template definition file. If the template definition file can be provided, the source file can be replayed, that is, all the functions and data ignored and only the types accessed.

This scheme is somewhat more flexible in its handling of types, with name mapping files no longer required. However, a different set of problems arises. One has to be able to determine the source file that the object file was created from. Another problem is performance; a source file after preprocessing may be a megabyte or more in length, and it is expensive to replay.

Preprocessor Macros and Pragmas

These manual schemes suffer from the disadvantages listed in the section above on manual instantiation.

Carrying Headers Along

One way to recover type information at link time is to carry all the required information along in the repository. That way, one does not have to worry about whether headers are available at link time. However, this approach has a very significant size cost. An alternative would be to "digest" the header and abstract its type information, but even this would result in large files.

Summary

We are aware of no template instantiation scheme that does not involve many tradeoffs. The above scheme, with its slight restrictions on header file usage, seems to offer the best compromise between ease of use, ease of implementation, portability, and performance.

Glossary

archive - a collection of object files typically grouped using the `ar` command. At link time, only object files that have needed symbols are extracted from the archive.

argument declaration file - a file containing the declaration of a class, struct, union, or enum type.

basename - the part of a UNIX™ pathname after the last /.

class template - a template that describes a family of types.

directed mode - a compiler mode that is used to generate an object file with certain specified template symbols defined in it.

external symbol - a name of a function or data item in an object file that is available to other object files to link against.

function template - a template that describes a family of functions.

header cache - a file in the repository used to store the list of headers needed by each instantiation.

instantiate - to form an instantiation by binding a template to particular argument types.

instantiation - a generated class or function that is the result of binding a template to particular argument types.

instantiation file - a source file that is compiled in directed mode to produce an object file instantiation.

library - same as **archive**.

name mapping file - a text file that describes which header files in an application define particular class, enum, and template types.

pre-linker - a tool that examines unresolved template references in object files and archives and creates an additional set of object files that resolve those references; the additional objects are fed into the link step.

repository - a directory that stores instantiations as object files, together with name mapping files.

specialization - an instantiation of a template class or function template that overrides the standard version.

template - a skeleton or description for a family of types or functions.

template argument - a type or constant specified to a template to distinguish a particular usage of the template.

template class - an instantiation of a class template for particular argument types.

template declaration file - a header file that declares a template interface.

template definition file - an implementation of a template's functions.

template function - an instantiated function template.

timestamp - the date and time a file was last changed.

Footnotes

1. While we are using file names that correspond to the class names, the instantiation scheme cannot force such a relationship between a class name and the name of the files that declare and/or define it. For example, a scheme that requires the declarations or definitions of `String` to be in `String.h` and `String.c` is unacceptable, because such a scheme makes it impossible to declare or define two templates in the same file. This scheme also obviously falls short in reflecting real-world naming conventions.

8 Template Instantiation – User Guide

Template Instantiation in C++ Release 3.0.1 – User Guide

NOTE This chapter is taken directly from a paper by Glen McCluskey.

Introduction

This chapter presents detailed information on use of the template instantiation environment with C++ Release 3.0.1. It assumes familiarity with the template section of *The Annotated C++ Reference Manual* (M.A. Ellis and B. Stroustrup, Addison-Wesley, 1990) and Chapter 7 of this document *Template Instantiation in C++ Release 3.0.1 - Overview.*

Getting Started

Suppose that you want to use vectors in an application, but find that the builtin ones in C++ are too restrictive. For example, they do not grow dynamically as new elements are added.

A first attempt to define a vector template might look like this:

```
template <class T> class Vector {
        T* data;
        int size;
public:
        Vector();
        T& operator[](int);
};
```

This declaration has two private data members `data` and `size` and two public functions `operator[]` and the constructor. There is one argument `T` to the template.

Assume that the declaration of the `Vector` template is in a file `Vector.h`. Then the implementation would be in a file `Vector.c` and would look like:

```
template <class T> Vector<T>::Vector()
{
        // start off with 10 elements

        size = 10;
        data = new T[size];
}
```

```
template <class T> T& Vector<T>::operator[](int n)
{
        int os;
        int i;
        T* newdata;

        // grow if have to


        if (n >= size) {
                os = size;
                while (size <= n)
                        size *= 2;
                newdata = new T[size];
                for (i = 0; i < os; i++)
                        newdata[i] = data[i];
                delete data;
                data = newdata;
        }

        // return reference to data slot

        return data[n];
}
```

Note that the implementation looks much like regular C++ code. The one difference is that the code is *parameterized,* that is, the implementation is relative to a type that is unknown but represented by T.

Finally, there is an application that uses this template:

```
#include <stream.h>
#include "Vector.h"

main()
{
        Vector<int> v;
        int i;

        // put data into vector
        for (i = 1; i <= 15; i++)
                v[i] = i * i;

        // pull it back out

        for (i = 1; i <= 15; i++)
                cout << i << "  " << v[i] << "\n";
}
```

Note that the `Vector` template has a type `int` substituted for the `T` we saw earlier. Note also that the vector `v` can be used transparently, without having to worry about increasing its size.

To compile this application, one would say:

```
$ CC appl.c
```

After `appl.c` is compiled, the `CC` compiler will go on to create an object file for the template class (template plus particular arguments) `Vector<int>`. The object will contain the members `Vector<int>::Vector()` and `Vector<int>::operator[](int)`. This process is known as *instantiation.*

To get an idea of the actions the compiler took, you can look in the *repository,* the area where the compiler stored the object file:

```
$ ls ./ptrepository
```

Besides the object file, there will be a `.c` (instantiation file), a `.cs` (checksum file), and the name mapping file `defmap`.

Coding Conventions

This section gives recommendations about how an application's files should be structured to make best use of templates.

Argument Declaration Files

An argument declaration file is used to declare types used as arguments to a template. For example, for the template class `Vector<A,B**>`, `A` and `B` are the underlying argument types. Fundamental types require no special declarations; for example, the types `int` or `unsigned short*`.

An argument type should be declared in one header file that is either self-contained or that includes other headers that it needs. If this is not possible then a map file needs to be written (see the section on map files, below). It is acceptable to have several types defined in one header. An example of a self-contained header would be:

```
#ifndef INCL_A
#define INCL_A
class A {
        int x;
public:
        void f();
        void g() {}
};
#endif
```

while one with other includes might look like:

```
#ifndef INCL_A
#define INCL_A
#include "Point.h"
class A {
        Point p[10];
public:
        void rotate(int);
};
#endif
```

`INCL_A` is an *include guard,* used to prevent the same file from being included more than once. Use of include guards is strongly recommended when writing template header files.

The C++ compiler extracts type information from headers and remembers it so that the instantiation process can get it back when needed. If a type has not been previously seen it is possible to use it only as a pointer or reference type, for example `Vector<A*,B&>`.

Template Declaration Files

A template declaration file is used to declare a template. It is like a class declaration in that the function and data members are laid out in the normal way. For example, a declaration file could contain:

```
template <class T> class AAA {
        T x;
        int y;
public:
        void f();
        void g(T&);
};
```

For function templates a forward declaration is used:

```
template <class T> void sort(T*, int n);
```

Function template external names resulting from instantiation are encoded the same as C++ functions. As such, a map file entry is the only way the instantiation system knows that an unresolved symbol might represent a template needing expansion, and the map file entry is created when a forward declaration is seen.

The template declaration file is the only template header file included by the user application; template definition files discussed in the next section are automatically included at instantiation time.

Like argument declaration files, a template declaration file should include header files it needs for types it uses. However, headers for types used as template arguments or the definition of the template itself should *not* be included, since these are handled automatically by the instantiation system.

Template Definition Files

The template definition file contains the implementation of a template. By convention, it is assumed that the definition file has the same name as the template declaration file, but with `.c` substituted for `.h` in the name. The case of the extension is preserved across the substitution. For example, `.H` is replaced with `.C`.

This convention can be overridden by map files (see the section below on map files). If the example of the previous section was declared in `AAA.h`, then the definition file would be `AAA.c`, and would look like:

```
template <class T> void AAA<T>::f() { /* ... */ }

template <class T> void AAA<T>::g(T&) { /* ... */ }
```

A definition file should not include the declaration file that matches it or the argument files that declare any template argument types. However, if include guards are consistently used, such inclusion is harmless. Including a guarded template definition file in a template declaration file will cause the definition file to be typechecked at application compile time, at the expense of a slower compile.

There must be a definition file for each declaration one, or else a map file written to override the standard convention. For a template type `T`, the declaration and definition files `T.h` and `T.c` are assumed if the files cannot be otherwise found. If a template definition file does not exist along the `-I` path, a warning is given and the file not included. All other missing files will cause a preprocessor error at instantiation time.

Inline Functions

Inline template member functions are treated similarly to their class counterparts. An inline can be declared and defined in the template declaration:

```
template <class T> struct A {
      void f() { /* ... */ }
};
```

or in the definition file:

```
template <class T> inline void A<T>::f() { /* ... */ }
```

The `inline` keyword is mandatory if the inline is defined outside the template declaration; if not used, the member will not be inlined.

NOTE In release 3.0, the inline must be defined in the template class body.

Types Defined in Application Sources

The instantiation system is best suited for types defined in header rather than source files. If you want to define types in source files, it is best to do it all or none. That is, fully define all templates and template argument types in one source file, or else define them all in headers.

Data and Functions in Template Files

Template declaration and definition files *are* header files, and should be treated as such. This means, for example, that a function or data item defined in such a header will probably be laid down in several instantiation files, leading to linker conflicts.

A static function (local to the file) will be duplicated in each instantiation. This is functionally correct but wasteful of space.

Static data items, as in:

```
static int x;
template <class T> int A<T>::f()
{
        int y = x++;
        return y;
}
```

are not supported, in part because it is not clear what such usage really means. The template definition file may be used several times, and the `x` variable is no longer local to the file. Static class members are a better choice in this case.

Summary of Coding Conventions

- Headers should be guarded against multiple inclusion.
- A header describing a type should be self-contained or include with include guards other headers that it needs.
- The name of a template definition file should be the same as the template declaration file, with `.h` replaced by `.c`.

- Function templates need a forward declaration.

All the following restrictions can be gotten around by use of map files.

Map Files

A map file can be used to overcome the restrictions noted in the previous section. The default map file is `defmap` in the repository, with `defmap.old` the previous version that is created every time the map file is rewritten. User-specified files start with the string `nmap` and are also placed in the repository. User-specified files take precedence over the default and are considered in alphabetical order. For example, `nmap001` is looked at before `nmap2`.

A map file entry might look like this:

```
@dec Vector app1 app2
<Vector2.h>
@def Vector app1 app2
<Vector2a.c>
<Vector2b.c>
```

This says that type `Vector` is declared in `Vector2.h` and defined (implemented) in `Vector2a.c` and `Vector2b.c`; the headers have standard `#include` semantics as specified by the type of quotes on the header name. The type is valid for the application files `app1` and `app2` (whether in source or object form, for example `app1.c` or `app2.o`).

Application files are recorded to handle the case where there are distinct applications sharing one repository. It is also possible to have map file entries with no application files specified; these entries serve as a last resort if the type cannot otherwise be found. Long lists of application names can be continued onto multiple lines by using the backslash character at the end of the line.

If only one of the `@dec` and `@def` entries for a type is specified in the file, then standard naming rules are used to derive the other header names. For example, without the `@def` entry above, the instantiation system would infer that `Vector` is defined in `Vector2.c`.

When the instantiation system writes the default map file, it compresses it by using a string table at the top of the file:

```
@tab
app1
app2
app3
app4
@etab
@dec A @0 @2
<A.h>
```

and then references application names using the notation `@nnn`. This notation is not required; you can spell out the application names.

In map files, operator function templates are encoded as described on page 125 of *The Annotated C++ Reference Manual*. For example, `operator<<` comes out as `__ls`. Note that function template types are recorded without argument information. This effectively coalesces overloaded functions into a single map file entry.

CC Options

The template instantiation system adds several options to `CC`. These are specified on the `CC` line or by setting the environment variable `PTOPTS`. For example, to permanently enable verbose mode, you would say:

```
export PTOPTS=-ptv (SysV)

setenv PTOPTS -ptv (BSD)
```

`-pta` says to instantiate a whole template class rather than only those members that are needed. There are performance issues around this discussed below.

`-ptn` changes the default instantiation behavior for one-file programs to that of larger programs, where instantiation is broken out separately and the repository updated. One-file programs normally have instantiation optimized so that instantiation is done into the application object itself. The process is described below in the section on usage scenarios for simple programs.

`-ptr`*pathname* specifies a repository, with `./ptrepository` the default. If several repositories are given, only the first is writeable, and the default repository is ignored unless explicitly named.

`-pts` causes instantiations to be split into separate object files, with one function per object (including overloaded functions), and all class static data and virtual functions grouped into a single object.

NOTE In release 3.0, `-pts` and `-pta` cannot be used together, that is, `-pts` can only be used to split up *needed* functions rather than *all* functions.

`-ptt` was used in Release 3.0 to alter dependency checking. It is now (Release 3.0.1 and later) an obsolete option.

`-ptv` turns on verbose or verify mode, which displays each phase of instantiation as it occurs, together with the elapsed time in seconds that phase took to complete. Use of this option is recommended if you are new to templates. With verbose mode, the reason an instantiation is done and the exact `CC` command used are displayed.

The preprocessor directives `-I` and `-D` work as they normally do, but must also be specified at link time, to pick up the various template and application type header files.

`+i` is not changed from previous usage. It causes the instantiation system to leave `..c` files in the repository.

Usage Scenarios

This section describes how the instantiation scheme can be used for different types of projects.

Simple Programs

By default, a one-file program that is to be compiled and linked (no `-c` option) causes the C++ compiler to instantiate everything it can into the object file for the program. This means that the link-time instantiation system is bypassed, if all templates and argument types are found within the program itself. This behavior can be disabled via the `-ptn` option, that is, the instantiation system will kick in even for simple programs.

Small and Medium Projects

A small project often operates out of one directory and with a single developer. Suppose that such a project wanted to use some templates from a directory of template headers `/usr/local/template/incl`. This would be done by saying:

```
$ CC -I/usr/local/template/incl -c file1.c
```

and at link time:

```
$ CC -I/usr/local/template/incl file1.o file2.o -o prog
```

with the `-I` directive required for the instantiation mechanism. The repository used here would be the default `./ptrepository`.

If there is more than one project in a directory, it is better to use an explicitly-named repository:

```
$ mkdir rep1

$ CC -I/usr/local/template/incl -ptrrep1 -c file1.c
```

as a means of better separating one project from another.

Repository Permissions

When the default repository is created, it is given the same permissions as the directory it is created within. This is done with the `chmod` system call, with a fatal error given if it cannot be done. The instantiation system also tries to change the group of the created directory using `chown`, but it is not a fatal error if this cannot be done. Permissions of already existing repositories are never changed.

After possibly setting directory permissions, the file creation mode mask is set using the system call `umask`; this is done by taking the 1's complement of the directory permissions.

What all this means is that a repository will be created with the same access as its parent directory, and files that are created in the repository will reflect this access. If a repository is to be shareable it must be explicitly changed to be so:

```
$ chmod 775 ptrepository
```

or it must be implicitly created in a directory with such permissions. The instantiation system deletes files in the repository before rewriting them, so if a repository has files in it and then the repository's permissions are changed, no access problems will come up.

Another approach is for team members to set the default creation mask at the shell level:

```
$ umask 002
```

Large Projects and Multiple Repositories

A large project often has the notion of a centralized set of files (sources, objects, libraries) plus a local work area for each developer. The idea is that the developer can use a combination of files from the central area plus the local one.

The best way to model this type of development is by multiple repositories. The instantiation system looks first in the local repository and then the central one, both for map files and instantiation objects. With such a scheme, a typical compilation line would read:

```
$ CC -I/usr/jones/tincl -I/usr/proj/tincl -I/usr/jones/incl \
    -I/usr/proj/incl -ptr/usr/jones/rep -ptr/usr/proj/rep -c file.c
```

Repository Management

The instantiation system adds to the repository but does not delete from it. Maintenance must be done by the user. For example, a `make` rule to completely delete the repository after a compile and link would look like:

```
appl:   appl1.o appl2.o
        CC appl1.o appl2.o -o appl
        rm -rf ./ptrepository
```

Of course, with this rule, instantiation must be repeated at every link.

Sharing Code and Use of Archives

Instantiations in a repository are simply object files, that are easily exportable into an archive. For example, with the default repository one can say:

```
$ ar cr projlib.a ./ptrepository/*.o
```

Such an archive may or may not be useful to other projects. By default, the system instantiates only what an application needs, and thus the object files will not contain all members of template classes. Another project with different needs will not be able to use such objects. Use of the `-pta` option (instantiate everything) will solve this problem at the expense of wasted binary size. A reasonable strategy might be to initially use `-pta` and turn it off later in a project cycle.

The option `-pts` may also be useful. It causes the instantiation system to split up instantiations, one function per object file. This reduces problems with object files clashing because they contain different but overlapping subsets of symbols.

Libraries

By the term *library* is meant a collection of object files, also known as an *archive*. This term is also used to denote collections of template headers, but such usage is confusing and not further discussed here.

Suppose that one has a library that uses templates, but end users of the library do not know or care about templates. How can the instantiation process be avoided for those users? The answer is to preinstantiate or form the *closure* of the library, that is, instantiate everything into object files and add the objects to the library.

To do this for a library `/usr/proj/lib.a`, one would say:

```
$ mkdir scr
$ cd scr
$ ar x /usr/proj/lib.a
$ CC -pts -I/usr/proj/tincl -I/usr/proj/incl *.o
$ rm -f /usr/proj/lib.a
$ ar cr /usr/proj/lib.a *.o ./ptrepository/*.o
```

This process will cause a link error from `CC` (because there is no `main` function) that can be ignored. `-pts` is specified so that the instantiation objects are split apart into separate files, which minimizes external symbol collisions when objects are linked with an application or another library.

Note that object file names in the repository may be longer than the 14 characters that `ar` will handle. The solution is to rename object files; a tool for this purpose is described in the section below on tools.

Dependency Checking

The instantiation system computes for each instantiation object the set of headers upon which it depends. This is done by running the preprocessor on the instantiation file. This set is called a *header cache* and is stored in the repository. It is updated when headers change.

An instantiation object is considered out of date if its timestamp is older than any of the headers in the cache for that object. This scheme is very similar to `make`, but does not require the user to express instantiation object dependencies in a makefile.

Sometimes it is desirable to get around dependency checking. To force reinstantiation, it is sufficient to simply delete all object files in the repository. The standard `make` trick of using `touch` to update the source or object modification times can also be used. For example, touching all object files in the repository will force off instantiation.

Specializations

A *specialization* is a means of overriding the standard version of a template class or a particular member of the class. This is done to get slightly different semantics or for performance. To illustrate how specializations work, consider this example:

```
// t1.h
// A template
template <class T> struct A {
      int f();
};

// t2.h
// B template
template <class T> struct B {
      int f();
      int g();
};

// t3.h
// f template
template <class T> int f(T);

// t1.c
// implementation of A
template <class T> int A<T>::f()
{
      return 37;
}

// t2.c
// implementation of B
template <class T> int B<T>::f()
{
      return 37;
}
template <class T> int B<T>::g()
{
      return 37;
}
```

```
// t3.c
// implementation of f
template <class T> int f(T t)
{
      return 83;
}

// A.h
// class specialization of A
struct A<int> {
      int f();
};

// A.c
// implementation of A<int> specialization
#include "t1.h"
#include "A.h"
int A<int>::f()
{
      return 47;
}

// B.c
// specialization of B<int>::g() - B<T>::f() unaffected
#include "t2.h"
int B<int>::g()
{
      return 47;
}

// f.c
// specialization of f
#include "t3.h"
int f(int t)
{
      return 57;
}
```

```
// main.c
#include "t1.h"
#include "A.h"
#include "t2.h"
#include "t3.h"
extern "C" void exit(int);
main()
{
        A<int> a;
        B<int> b;

        if (a.f() != 47)
                exit(1);
        b.f();

        if (b.g() != 47)
                exit(2);

        f(1234L);
        if (f(83) != 57)
                exit(3);
        exit(0);
}
```

There are three templates `A`, `B`, and `f`. The template class `A<int>` is completely specialized by the declaration and definition in `A.h` and `A.c`. `B.c` defines a specialization for `B<int>::g`, and `f.c` a specialization `f(int)`. Note that when a complete template class is specialized, the class must be defined before use.

To compile and link this application, one would say:

```
$ CC -c A.c
$ CC -c B.c
$ CC -c f.c
$ CC main.c A.o B.o f.o
```

The compiled specializations must be placed on the link line to prevent the general versions from being instantiated at link time. For example, if `f.o` had not been placed on the `CC` line, the specialized version of `f(int)` would not have been used.

Specialization of static template class data members is done in a similar way. A template declaration may provide a general template initializer:

```
template <class T> int A<T>::x = 97;
```

To specialize this, one would say:

```
int A<int>::x = 52;
```

somewhere in the application.

Debugging Instantiations

A debug option such as `-g` is passed by `CC` through to `ptlink` to the call to `CC` to instantiate. Debugging is therefore automatically enabled for instantiations.

One thing can go wrong with debugging, however. If a repository pathname is specified, and it is not fully qualified, then the debugger will fail to find the source files if the application binary is moved relative to the repositories used to build it. This is easily fixed by giving full pathnames for repositories. For example:

```
$ CC -ptr/usr/xxx/ptrepository appl.c
```

There may be problems with individual debuggers, however. If you set a breakpoint on a source line of a template definition file, this sets up a many-to-one relationship between the instantiations and the source. For example, the instantiation objects for `Vector<A>` and `Vector<B>` will both refer to the header file `Vector.c`. Another way of saying it is that there is no current way to debug individual instantiations.

Performance

Performance of the instantiation scheme is almost purely a function of how much instantiation is done. Manipulating map files and other housekeeping contributes little to the total cost.

The simplest way to cut down instantiation costs is to avoid instantiation. This is done by *anticipating* the need for template classes, and supplying them in archive (library) form at link time; object files could be migrated out of the repository into an archive for this purpose. This implies that such template classes change infrequently. If template classes *do* change frequently, there is an intrinsic cost to be paid in reinstantiation. As a rule of thumb, migration should be considered if there are more than about 15 - 20 objects in the repository.

Another important aspect of performance is minimizing iteration during instantiation. For example, with the default behavior of instantiating only what is needed, a member `A<int>::f` might be needed in an application. This member may in turn need `A<int>::g`, causing another iteration to occur in the instantiation loop. In general there is no way to determine in advance what the instantiation dynamics will be, short of an intimate understanding of one's application.

The compiler option `-pta` can be used to instantiate a whole template class rather than simply those members that are needed. This will prevent iteration on the class members, but may cause another type of iteration, where unused members cause a demand for members of some other template class. Some experimentation will be necessary to determine the best option to use in a given case.

Streamlining the Non-template Case

There is no easy way to tell whether an application uses templates, so the instantiation mechanism must cast its net widely. If the default repository exists and has a non-empty `defmap` file in it, the pre-linker is called.

The pre-linker in turn calls `nm` for each object and archive. If this does not turn up any unresolved template symbols, linking is then done. So in the worst non-template case `nm` is called once for each file.

The simplest way to avoid any overhead at all is to delete the default repository from the current directory.

Interpreting Errors

Errors and warnings coming from the instantiation system will have either the string:

```
CC[ptcomp]
```

or the string:

```
CC[ptlink]
```

in front of them. Other errors will be from the C++ compiler itself or the linker.

What Can Go Wrong

Timestamps on Networks of Workstations

Like `make`, dependency analysis relies on modification timestamps to determine if an object file (an instantiation) is out of date. If you have a network of workstations, it is possible that timestamps will be out of sync because file modification times may be set from different clocks on different file servers. In such a case timestamps will not compare and dependency checking will not work correctly.

There is nothing that the instantiation system can do about this problem. It must be solved by system administration. There are often schemes available to continually synchronize workstation clocks with each other.

External Name Length Limitations

The instantiation scheme examines the symbol tables of object files to get a list of template symbols used to drive the instantiation process. These symbol names must fully describe the template class used by a given function or data item. Some systems have a name length limit of 8 or 32, which will not work. Other systems have a limit of 256, which is usually adequate.

Note that typedefing a long class name or template class name to shorten it will not fix this problem, since the typedef name is expanded to the underlying types when external names are encoded.

Map File Problems

A map file contains type/header pairs for one or more programs. For example, an entry such as:

```
@dec T app1 app2
"U.h"
```

says that type `T` is defined in `U.h` and is valid for the files app1 and app2.

If you have many distinct programs that use the same type names, then the default map file will become very large. This is only likely to occur if there are many programs in one directory, for example, test cases that all use the type `T`. The map file can be compressed using a string table (see the section above describing map files).

Another problem is slowly accumulating garbage in map files. An effort is made to delete out-of-date information when a file is recompiled, but this process is not perfect.

Violation of the One Definition Rule

Because of separate compilation, the C++ compiler will accept usage such as:

```
// file 1
struct A {};

// file 2
template <class T> struct A {};
```

even though this is a violation of the One Definition Rule. Because type mapping information is collected into one file, the instantiation system will catch many such errors. The form of the error is:

```
fatal error: type A defined twice in map files
```

Picking Up the Wrong Versions of Headers

Some source code control and configuration management systems support named versions of source files and headers, and program compilation is done with particular sets of versions of files (a configuration). Template instantiation does not cause any problems with this, but one must be sure that the same versions of files are specified via `-I` at *link* time as are given at *compile* time.

Replaying Source Files

If a source file looks like:

```
// main.c

#include <Vector.h>

struct A {};
```

```
main()
{
        Vector<A> a;

        a.f();
}
```

and `Vector.h` does not have include guards, then it will end being included twice, once to get at the type `Vector` and once as an indirect result of including `main.c` to get at the type `A`.

The workaround for this is either to use include guards or else completely define the types in `main.c` or completely define them in header files.

Function Templates

A function template is encoded just like a C++ function. At instantiation time there is no way to tell them apart. Therefore, the instantiation system tries to instantiate function templates only if an entry is found for them in the map files. This entry will not be there unless a forward declaration:

```
template <class T> void f(T);
```

has been seen.

Another problem occurs if only a function *definition* is given in a single-file application, and then `-ptn` or `-c` is used to tell the instantiation system not to instantiate on the fly:

```
template <class T> void f(T) {}

main()
{
        f(37);
}

$ CC -ptn prog.c
```

Because there is no *declaration,* no entry is made in the map file, resulting in an unresolved global `f(int)` at link time. The workaround is to use a declaration or not use `-ptn`.

Finally, a problem can occur with specializations of function templates and argument matching. Suppose that there is a function template:

```
template <class T> void f(Vector<T>&);
```

and a declaration of a specialization:

```
void f(char*);
```

Further suppose that the specialization is not defined anywhere and so is found to be unresolved by the pre-linker. The pre-linker will look for `f` in the map files and find it, and will therefore conclude that it is a template to be instantiated. It will then attempt to instantiate with a `char*` argument to the `f(Vector<T>&)` template, with disastrous results.

Static Data Member Initialization

The instantiation system considers that the tentative definition (global common) that the C++ compiler emits for each static data member of a template class represents an *undefined* external symbol that must be defined and initialized somewhere. For example:

```
template <class T> struct A {
      static int x;
};
```

by itself would result in an unresolved external.

This usage follows the C++ standard, but the C++ compiler has not enforced it up to now.

An initializer might look like:

```
template <class T> int A<T>::x = 47;
```

or:

```
int A<char*>::x = 89;
```

The first of these is a general template initializer, the second a specialization.

Type Checking of Template Members

By default, only members of a template class that are used are instantiated. Other members are not typechecked and therefore legally could contain errors. For overloaded functions, all versions of the function are instantiated so long as at least one of them is used. So if one overloaded function is called and the other contains errors, instantiation will not succeed. All virtual functions are instantiated because there is no way to tell whether they are needed.

If you use the `-pta` option, or compile a one-file program, the C++ compiler will try to instantiate all members of needed template classes, with potential errors.

`nm` Problems

The utility `nm` is used to extract the symbol tables from objects and archives. There is at least one case where `nm` can fail without it being a fatal error, and that is for an object file containing no functions or data. An `nm` failure therefore elicits only a warning and not an error, with the contents of the object or archive ignored.

Another obscure problem comes up if `main` is defined in an archive rather than an object file; the start up program `/lib/crt0.o` is not considered in pre-linking, and thus there is no demand for `main`.

Renaming Object Files

The basename of an object file is used to validate type entries in map files. If the name changes, the type entry will be invalid unless other object files specified along with the renamed one are also found on the basename list in the map file.

The simplest solution to this problem is to write a map file with a type entry containing no list of basenames (see description of map files above).

Debug and Large Binaries

The instantiation system creates one object file for each template class. With some debug formats, the linker does not merge duplicated strings and other debug information occurring in several object files. This can cause a large blowup in binary size. The problem has no easy solution.

Source File Extensions

When the instantiation system is built, the extensions for source, header, and object files can be specified, with defaults of `.c`, `.h`, and `.o` respectively. Once configured, these extensions are fixed, with one exception.

The exception is the rule that case is preserved when replacing a header extension (for a template declaration file) with a source extension (for a template definition file). For example, if a template `Vector` is declared in `Vector.H`, then the definition is assumed to be in `Vector.C`.

Tools

Because the repository is a UNIX™ directory and the files in it are not special in any way, it is possible to use standard utilities in various ways to get at information. For example, consider a system that has only 14-character filenames. Hash codes are used to name files in place of complete mangled names, and it would be nice to come up with a correspondence list showing which hash code maps to what template name.

A shell script to do this is:

```
#!/bin/sh

# display the template class for each instantiation file
# in the repository

PATH=/bin:/usr/bin:/usr/ucb

pn='basename $0'
rep=$1
if [ "$rep" = "" -o ! -d "$rep" ]
then
      echo "usage: $pn repository" 1>&2
      exit 1
fi

cd $rep
ls *.c |
while read fn
do
      n='sed -n '1s/^\/\* \(.*\) \*\/$/\1/p' $fn'
      echo "$fn  -->  $n"
done

exit 0
```

Another tool can be used to package the object files in a repository into an archive, with renaming to short names for `ar`:

```
#!/bin/sh

# export contents of repository into an archive

PATH=/bin:/usr/bin:/usr/ucb

pn='basename $0'

t=/tmp/$pn.$$
trap "rm -rf $t; exit 2" 1 2 3 15
rm -rf $t
mkdir $t

if [ $# -ne 2 -o ! -d "$1" ]
then
      echo "usage: $pn repository archive"
      exit 1
fi

n=1
for i in $1/*.o
do
      cp $i $t/${n}.o
      n='expr $n + 1'
done

rm -f $2
ar cr $2 $t/*.o
if [ -x /bin/ranlib -o -x /usr/bin/ranlib ]
then
      ranlib $2
fi

rm -rf $t

exit 0
```

These tools are included in the distribution.

Examples

This section will walk through a few small example cases.

Single File (Hello World) Case

In the simplest case, the template definition and the application code that uses it are all in the same file:

userapp.c:

```
#include "String.h"

template <class T>
class Stack {
        T* head;
public:
        Stack() : head(0) {}
        T pop();
        void push(T&);
};

template <class T> T Stack<T>::pop()
{
/* ... */
}

template <class T> void Stack<T>::push(T& arg)
{
/* ... */
}


main()
{
        Stack<String> s;
        /* Code that uses push and pop */
}
```

The following steps describe how the instantiation works in this case. However, all this is done behind the scenes; in the normal case, the user will simply say

```
CC userapp.c
```

and the right thing will happen automatically.

1. When `userapp.c` is compiled to an object file, the references to `Stack<String>::push(String&)` and `Stack<String>::pop()` will be compiled as normal function calls. Since `Stack<String>::Stack()` is inline, no reference to that function is generated.
2. As a side effect of compiling `userapp.c` to an object file, the name mapping file is updated to show the declaration of templates and classes:

   Name mapping file (defmap):

   ```
   @dec String userapp
   "String.h"
   @dec Stack userapp
   "userapp.c"
   ```

3. Because a single file is being compiled and linked, instantiation will occur by default into the application file, and the repository will not be updated.

Separate Compilation

More commonly, the template will be declared in a header file, with the definitions provided in a separate file:

Stack.h:

```
template <class T>
class Stack {
        T* head;
public:
        Stack() : head(0) {}
        T pop();
        void push(T&);
};
```

Stack.c:

```
template <class T> T Stack<T>::pop()
{
/* ... */
}
```

```
template <class T> void Stack<T>::push(T& arg)
{
/* ... */
}
```

userapp.c:

```
#include "String.h"
#include "Stack.h"

main()
{
      Stack<String> s;
      /* Code that uses push and pop */
}
```

Here, the scenario is the same as before, except that the template declaration and definition will be gotten from a different place. The name mapping file after compiling `userapp.c` will be:

Name mapping file (defmap):

```
@dec String userapp
"String.h"
@dec Stack userapp
"Stack.h"
```

Since the template declaration file is `Stack.h`, the definition file will be `Stack.c`. The automatically generated instantiation file will be:

```
#include "Stack.h"  // Template decl file
#include "Stack.c"  // Template defn file
#include "String.h" // Arg decl file
```

Of course, `Stack.c` must be available along the `-I` path in order for the instantiation to succeed.

An advantage of this structure is that the template definition file (`Stack.c`) does not have to be parsed with user application code; it need only be parsed when templates are being instantiated.

The first steps in the procedure are as before, and then the pre-linker does its work.

1. At link time, the pre–linker will determine that the following functions must be instantiated:

   ```
   Stack<String>::push(String&)
   Stack<String>::pop()
   ```

2. The repository is checked for an object file that contains these instantiations. If there is one, and it is up to date with regard to its headers, we add that file to the list of files to be linked, and go to step 4.
3. If the repository does not contain an up-to-date object file with these instantiations, we must instantiate them now. Since we are using the default granularity, both members of `Stack<String>` will be instantiated into the same object file. The template declaration file (from the name mapping file) is `Stack.h`. The template definition file has the same name as the template declaration file, except that the suffix (if any) is changed to `.c`; here, the template definition file is `Stack.c`. The argument declaration file (also from the name mapping file) is `String.h`.

   Directed instantiation is used; the compiler builds an object file that contains the definitions of `Stack<String>::push(String&)` and `Stack<String>::pop()`, plus any virtual functions in `Stack<String>`.
4. The resulting object file is put in the repository, and the pre-linker iterates (since the member functions of `Stack<String>` might themselves refer to other templates). If there are any new instantiations needed, we repeat the above process.
5. If the pre-linker is satisfied that all required object files are available, the linker is called to complete the link.

Again, remember that this all happens behind the scenes; for this simple case, users need not be aware of the template instantiation details, except that any -I flags passed at compile time must also be passed at link time.

Separate Compilation, Special Case Provided At Link Time

It is legal for a special case of a template member to be discovered at link time. For example, in the previous case, suppose this additional file were provided at link time:

stringpop.c:

```
#include "String.h"
#include "Stack.h"

/* Special case version of Stack<String>::pop */

void Stack<String>::pop()
{
/* ... */
}
```

Here, the pre-linker would determine that only `Stack<String>::push(String&)` was required, and only that function would be instantiated. Note that this will work properly even if the general version of `Stack<String>::pop()` would not compile; since we did not need the general version, we did not try to compile it.

9 Type-Safe Linkage for C++

Type-safe Linkage for C++

NOTE This chapter is taken directly from a paper by Bjarne Stroustrup.

Abstract

This paper describes the problems involved in generating names for overloaded functions in C++ and in linking to C programs. It also discusses how these problems relate to library building. It presents a solution that provides a degree of type-safe linkage. This eliminates several classes of errors from C++ and allows libraries to be composed more freely than has hitherto been possible. Finally the current encoding scheme for C++ names is presented.

Introduction

This paper describes the type-safe linkage scheme used by the 2.1 release of C++ and the mechanism provided to allow traditional (unsafe) linkage to non-C++ functions. It describes the problems with the scheme used by previous releases, the alternative solutions considered, and the practicalities involved in converting from the old linkage scheme to the new.

The new scheme makes the `overload` keyword redundant, simplifies the construction of tools operating on C++ object code, makes the composition of C++ libraries simpler and safer, and enables reliable detection of subtle program inconsistencies. The scheme does not involve any run-time costs and does not appear to add measurably to compile and link time.

The scheme is compatible with older C++ implementations for pure C++ programs but requires explicit specification of linkage requirements for linkage to non C++ functions.

The Original Problem

C++ allows overloading of function names; that is, two functions may have the same name provided their argument types differ sufficiently for the compiler to tell them apart. For example,

```
double sqrt(double);
complex sqrt(complex);
```

Naturally, these functions must have different names in the object code produced from a C++ program. This is achieved by suffixing the name the user chose with an encoding of the argument types (the *signature* of the function). Thus the names of the two `sqrt()` functions become:

```
sqrt__Fd          // the sqrt that takes a double argument
sqrt__F7complex   // the sqrt that takes a complex argument
```

Some details of the encoding scheme are described under "The Function Name Encoding Scheme."

When experiments along this line began five years ago it was immediately noticed that for many sets of overloaded functions there was exactly one function of that name in the standard C library. Since C does not provide function name overloading there could not be two. It was deemed essential for C++ to be able to use the C libraries without modification, recompilation, or indirection. Thus the problem became to design an overloading facility for C++ that allowed calls to C library functions such as `sqrt()` even when the name `sqrt` was overloaded in the C++ program.

The Original Solution

The solution, as used in all non-experimental C++ implementations up to now, was to let the name generated for a C++ function be the same as would be generated for a C function of the same name wherever possible. Thus `open()` gets the name `open` on systems where C doesn't modify its names on output, the name `_open` on systems where C prepends an underscore, etc.

This simple scheme clearly isn't sufficient to cope with overloaded functions. The keyword `overload` was introduced to distinguish the hard case from the easy one and also because function name overloading was considered a potentially dangerous feature that should not be accidentally or implicitly applied. In retrospect this was a mistake.

To allow linkage to C functions the rule was introduced that only the second and subsequent version of an overloaded function had their names encoded. Thus the programmer would write

```
overload sqrt;
double sqrt(double);                // sqrt
complex sqrt(complex);              // sqrt__F7complex
```

and the effect would be that the C++ compiler generated code referring to `sqrt` and `sqrt__F7complex`. This enabled a C++ programmer to use the C libraries. This trick solves the problems of name encoding, linkage to C, and protection against accidental overloading, but it is clearly a hack. Fortunately, it was only documented in the "BUGS" section of the C++ manual page.

Problems with the Original Solution

There are at least three problems with this scheme:

- how to name `overloaded` functions so that one may be a C function
- how to detect errors caused by inconsistent function declarations
- how to specify libraries so that several libraries can be easily used together

The `overload` Linkage Problem

Consider a program that uses an overloaded function `print()` to output `globs` and `widgets`. Naturally `globs` are defined in `glob.h` and `widgets` in `widget.h`. A user writes

```
// file1.c:
#include <glob.h>
#include <widget.h>
```

but this elicits an error message from the C++ compiler since `print()` is declared twice with different argument types. The user then modifies the program to read

```
// file1.c:
overload print;
#include <glob.h>
#include <widget.h>
```

and all is well until someone in some other part of the program writes

```
// file2.c:
overload print;
#include <widget.h>
#include <glob.h>
```

This fails to link since `file1.c`'s output refers to `print` (meaning `print(glob)`) and `print__F6widget`, whereas `file2.c`'s output refers to `print` (meaning `print(widget)`) and `print__F4glob`.

This is of course a nuisance, but at least the program fails to link and the programmer can — after some detective work based on relatively uninformative linker error messages — fix the problem. The nastier variation of this will happen to the conscientious programmer who knows that `print()` is overloaded and inserts the appropriate `overload` declarations, but happens to use only one variation of `print()` in each of two source files:

```
// file1.c:
overload print;
#include <glob.h>

// file2.c:
overload print;
#include <widget.h>
```

The output from `file1.c` and `file2.c` now both refer to `print`. Unfortunately, in the output from file1.c `print` means `print(glob)` whereas `print` refers to `print(widget)` in the output from file2.c. One might expect linkage to fail because `print()` has been defined twice. However, on most systems this is not what happens in the important case where the definitions of `print(glob)` and `print(widget)` are placed in libraries. Then, the linker simply picks the first definition of `print()` it encounters and ignores the second. The net effect is that calls (silently) go to the wrong version of `print()`. If we are lucky, the program will fail miserably (core dump); if not, we will simply get wrong results.

The requirement that the overload keyword must be used explicitly and the non-uniform treatment of overloaded functions ("the first overloaded function has C linkage") is a cause of complexity in C++ compilers and in other tools that deal with C++ program text or with object code generated by a C++ compiler.

The General Linkage Problem

This problem of inconsistent linkage is a variation of the general problem that C provides only the most rudimentary facilities for ensuring consistent linkage. For example, even in ANSI C and in C++ (until now) the following example will compile and link without warning:

```
#include <stdio.h>
extern int sqrt(int);

main()
{
          printf("sqrt(%d) == %d\m",2,sqrt(2));
}
```

and produce output like this

```
sqrt(2) == 0
```

because even though the user clearly specified that an integer `sqrt()` was to be used, the C compiler/linker uses the double precision floating point `sqrt()` from the standard library. This problem can be handled by consistent and comprehensive use of correct and complete header files. However, that is not an easy thing to achieve reliably and is not standard practice. The traditional C and C++ compiler/linker systems do not provide the programmer with any help in detecting errors, oversights, or dangerous practices.

These linkage problems are especially nasty because they increase disproportionately with the size of programs and with the amount of library use.

Combining Libraries

The standard header `complex.h` overloads `sqrt()`:

```
// complex.h:
overload sqrt;
#include <math.h>
complex sqrt(complex);
```

Some other header, `3d.h`, declares `sqrt()` without overloading it:

```
// 3d.h:
#include <math.h>
```

Now a user wants both the 3d and the complex number packages in a program:

```
#include <3d.h>
#include <complex.h>
```

Unfortunately this does not compile because of this sequence of operations:

```
double sqrt(double);        // from <3d.h>
overload sqrt;              // from <math.h> via <complex.h>
```

A function must be overloaded before its first declaration is processed. So the programmer, who really did not want to know about the internals of those headers, must reorder the #include directives to get the program to compile:

```
#include <complex.h>
#include <3d.h>
```

This will work unless `3d.h` overloads some function, say `atan()`, that `complex.h` does not. Even in that case the programmer can cope with the problem by adding sufficient `overload` declarations where `3d.h` and `complex.h` are included:

```
overload sqrt;
overload atan;
#include <3d.h>
#include <complex.h>
```

This reordering and/or adding of `overload` declarations is work that is really quite spurious and in any case irrelevant to the job the programmer is trying to do. Worse, if the extra `overload` declarations were placed in a header file the programmer has now set the scene for the users of the new package to have exactly the same problems when they try combining this new library with other libraries. It becomes tempting to overload all functions or at least to provide header files that overload all interesting functions. This again defeats any real or imagined benefits of requiring explicit `overload` declarations.

A General Solution

The overloading scheme used for C++ (until now) interacts with the traditional C linkage scheme in ways that bring out the worst in both. Overloading of function names that was introduced to provide notational convenience for programmers is becoming a noticeable source of extra work and complexity for builders and users of libraries. Either the idea of overloading is bad or else its implementation in C++ is deficient. The insecure C linkage scheme is a source of subtle and not-so-subtle errors. In summary:

- lack of type checking in the linker causes problems
- use of the `overload` keyword causes problems
- we must be able to link C++ and C program fragments

A solution to 1 is to augment the name of *every* function with an encoding of its signature. A solution to 2 is to cease to require the use of `overload` (and eventually abolish it completely). A solution to 3 is to require a C++ programmer to state explicitly when a function is supposed to have C-style linkage.

The question is whether a solution based on these three premises can be implemented without noticeable overhead and with only minimal inconvenience to C++ programmers. The ideal solution would

- require no C++ language changes
- provide type-safe linkage
- allow for simple and convenient linkage to C
- not break existing C++ code
- allow use of (ANSI style) C headers
- provide good error detection and error reporting
- be a good tool for library building
- not impose run-time overhead
- not impose compile time overhead

We have not been able to devise a scheme that fulfills all of these criteria strictly, but the adopted scheme is a good approximation.

Type-safe C++ Linkage

First of all, every C++ function name is encoded by appending its signature. This ensures that a program will only load provided every function that is called has a definition and that the type specified at the point of call is the same as the type specified at the point of definition. For example, given:

```
f(int i) { ... }                  // f__Fi
f(int i, char* j) { ... }         // f__FiPc
```

These examples will cause correct linkage:

```
extern f(int);                    // f__Fi   - links to f(int)
f(1);

extern f(int,char*);              // f__FiPc - links to f(int,char*)
f(1,"asdf");
```

These examples will cause linkage errors independent of where in the program they occur because no `f()` with a suitable signature has been defined:

```
// no declaration of f() in this file
// (this is only legal in C programs)
f(1);               // f      - links to ???

extern f(char*);    // f__FPc - links to ???
f("asdf");

extern f(int ...);// f__Fie - links to ???
f(1,"asdf");
```

One might consider extending this encoding scheme to include global variables, etc., but this does not appear to be a good idea since that would introduce at least as many problems as it would solve. For example:

```
// file1.c:
int aa = 1;
extern int bb;


//file2.c:
char* aa = "asdf";// error: aa is declared int in file1.c
extern char* bb;  // error: bb is declared int in file1.c
```

Under the current C scheme, the double definition of aa will be caught and the inconsistent declarations of bb will not. Using an encoding scheme, the double definition of aa would not be caught since the difference in encoding would cause *two* differently named objects to be created — contrary to the rules of C and C++. The fact that the inconsistent declarations of bb would be caught by some linkers (not all) does not compensate for the incorrect linkage of aa. Consequently only functions are encoded using their signatures.

This linkage scheme is much safer than what is currently used for C, but it is not meant to solve all linkage problems. For example, if two libraries each provides a function f(int) as part of their public interface there is no mechanism that allows the compiler to detect that there are supposed to be two different f(int)s. If the .o files are loaded together the linker will detect the error, but where a library search mechanism is employed the error may go undetected.

Note that this linking scheme simply enforces the C++ rules that every function must be declared before it is called and that every declaration of an external name in C++ must have exactly the same type.

In essence, we use the name encoding scheme to "trick" the linker into doing type checking of the separately compiled files. More comprehensive solutions can be achieved by modifying the linker to understand C++ types. For example, a linker could check the types of global data objects and might also be able to provide features for ensuring the consistency of global constants and classes. However, getting an improved linker into use is typically a hard and slow process. The scheme presented here is portable across a great range of systems and can be used immediately.

Implicit Overloading

If a function is declared twice with different argument types it is overloaded. For example:

```
double sqrt(double);
complex sqrt(complex);
```

is accepted without any explicit `overload` declaration. Naturally, `overload` declarations will be accepted in the foreseeable future; they are simply not necessary any more.

Does this relaxation of the C++ rules cause new problems? It does not appear to be the case. For example, originally I imagined that obvious mistakes such as

```
double sqrt(double);            // sqrt__Fd
double d = sqrt(2.3);

double sqrt(int d) { ... }      // sqrt__Fi
```

would cause hard-to-find errors. It certainly would with the traditional C linkage rules, but with type-safe linkage the program simply will not link because there is no function called `sqrt__Fd` defined anywhere. Even the standard library function will not be found because its name is `sqrt` as always.

Another imagined problem was that a call

```
f(x);
```

would suddenly change its meaning when a function became overloaded by the inclusion of a new header file containing the declaration of another function `f()`. This is not the case, because the C++ ambiguity rules ensure that the introduction of a new `f()` will either leave the meaning of `f(x)` unchanged (the new `f()` was unrelated to the type of `x`) or will cause a compile time error because an ambiguity was introduced.

C Linkage

This leaves the problem of how to call a C function or a C++ function "masquerading" as a C function. To do this a programmer must state that a function has C linkage. Otherwise, a function is assumed to be a C++ function and its name is encoded. To express this an extension of the "extern" declaration is introduced into C++:

```
extern "C" {
        double sqrt(double);        // sqrt(double) has C linkage
}
```

This linkage specification does not affect the semantics of the program using `sqrt()` but simply tells the compiler to use the C naming conventions for the name used for `sqrt()` in the object code. This means that the name of *this* `sqrt()` is `sqrt` or `_sqrt` or whatever is required by the C linkage conventions on a given system. One could even imagine a system where the C linkage rules were the type-safe C++ linkage rules as described above so that the name of `sqrt()` was `sqrt__Fd`. Linkage specifications nest, so that if we had other linkage conventions such as Pascal linkage we could write:

```
                                        // default: C++ linkage here
    extern "C" {
                                        // C linkage here
            extern "Pascal" {
                                        // Pascal linkage here
                    extern "C++" {
                                        // C++ linkage here
                    }
                                        // Pascal linkage here
            }
                                        // C linkage here
    }
                                        // C++ linkage here
```

Such nestings will typically only occur as the result of nested `#includes`.

The `{}` in a linkage specification does *not* introduce a new scope; the braces are simply used for grouping. This strongly resembles the use of `{}` in enumerations.

The keyword `extern` was used because it is already used to specify linkage in C and C++. Strings (for example, "`C`" and "`C++`") were chosen as linkage specifiers because identifiers (e.g., `C` and `Cplusplus`) would de facto introduce new keywords into the language and because a larger alphabet can be used in strings.

Naturally, only one of a set of overloaded functions can have C linkage, so the following causes a compile time error:

```
    extern "C" {
            double sqrt(double);
            complex sqrt(complex);
    }
```

Note that C linkage can be used for C++ functions intended to be called from C programs as well as for C functions. In particular, it is necessary to use C linkage for C++ functions written to implement standard C library functions for use by C programs. However, using the encoded C++ name from C preserves type-safety at link time. This technique can be valuable in other languages too. I have already seen an example of the C++ scheme applied to assembly code to prevent nasty link errors for low level routines. One might consider using this C++ linkage scheme for C also, but I suspect that the sloppy use of type information in many C programs would make that too painful.

In an "all C++" environment no linkage specifications would be needed. The linkage mechanism is intended to ease integration of C++ code into a multi-lingual system.

Caveat

One could extend this linkage specification mechanism to other languages such as Fortran, Lisp, Pascal, PL/1, etc. The way such an extension is done should be considered very carefully because one "obvious" way of doing it would be to build into a C++ compiler the full knowledge of the type structure and calling conventions of such "foreign" languages. For example, a C++ compiler *might* handle conversion of zero terminated C++ strings into Pascal strings with a length prefix at the call point of function with Pascal linkage and *might* use Fortran call by reference rules when calling a function with Fortran linkage, etc.

There are serious problems with this approach:

- The complexity and speed of a C++ compiler could be seriously affected by such extensions.
- Unless an extension is widely available, accepted programs using it will not be portable.
- Two implementations might "extend" C++ with a linkage specification to the same "foreign" language, say Fortran, in different ways so as to make identical C++ programs have subtly different effects on different implementations.

Naturally, these problems are not unique to linkage issues or to this approach to linkage specification.

I conjecture that in most cases linkage from C++ to another language is best done simply by using a common and fairly simple convention such as "C linkage" plus some standard library routines and/or rules for argument passing, format conversion, etc., to avoid building knowledge of non-standard calling conventions into C++ compilers. This ought to be simpler from C++ than from most other languages. For example, reference type arguments can be used to handle Fortran argument passing conventions in many cases and a Pascal string type with a constructor taking a C style string can trivially be written. Where extensions are unavoidable, however, C++ now provides a standard syntax for expressing them.

Experience

The natural first reaction to this scheme is to look for a way of handling linkage and overloading without requiring explicit linkage specifications. We have not been able to come up with a system that enabled C linkage to be implicit without serious side effects. I will summarize the advantages of the adopted scheme here and discuss several possible objections to it. "Alternative Solutions" below describes alternative schemes that were considered and rejected.

Making Linkage Specifications Invisible

One obvious advantage of this scheme is that it allows a programmer to give a set of functions C linkage with a single linkage specification without modifying the individual function declarations. This is particularly useful when standard C headers are used. Given a C header (that is, an ANSI C header with function prototypes, etc.)

```
// C header:
// C declarations
```

one can trivially modify the header for use from C++:

```
// C++ header:

extern "C" {
         // C header:
         // C declarations
}
```

This creates a C++ header that cannot be shared with C.

Sharing with C can be achieved using `#ifdef`:

```
// C and C++  header:

#ifdef __cplusplus
extern "C" {
#endif
         // C header:
         // C declarations
#ifdef __cplusplus
}
#endif
```

where `__cplusplus` is defined by every C++ compiler.

In cases where one for some reason cannot or should not modify the header itself one can use an indirection:

```
// C++ header:

extern "C" {
#include "C_header"
}
```

Fortunately, such transformations can be done by trivial programs so that most of the effort in converting C headers need not be done by hand.

It was soon discovered that even though programmers tend to scatter function declarations throughout the C++ program text, most C functions actually come from well defined C libraries for which there are — or ought to be — standard header files.

Placing all of the necessary linkage specifications in standard header files means that they are not seen by most users most of the time. Except for programmers studying the details of C library interfaces, programmers installing headers for new C libraries for C++ users, and programmers providing C++ implementations for C interfaces, the linkage specifications are invisible.

Error Handling

The linker detects errors, but reports them using the names found in the object code. This can be compensated for by adding knowledge about the C++ naming conventions to the linker or (simpler) by providing a filter for processing linker error messages. This output was produced by such a filter:

```
C++ symbol mapping:

PathListHead::~PathListHead()         __dt__12PathListHeadFv
Path_list::sepWork()                  sepWork__9Path_listFv
Path::pathnorm()                      pathnorm__4PathFv
Path::operator&(Path&)                __ad__4PathFR4Path
Path::first()                         first__4PathFv
Path::last()                          last__4PathFv
Path::rmfirst()                       rmfirst__4PathFv
Path::rmlast()                        rmlast__4PathFv
Path::rmdots()                        rmdots__4PathFv
Path::findpath(String&)               findpath__4PathFR6String
Path::fullpath()                      fullpath__4PathFv
```

Bringing this filter into use had the curious effect of replacing the usual complaint about "ugly C++ names" with complaints that the linker didn't provide sufficient information about C functions and global data objects.

The reason for presenting the encoded and unencoded names of undefined functions side by side is to help users who use tools, such as debuggers, that haven't yet been converted to understand C++ names.

A plain C debugger such as `sdb`, `dbx`, or `codeview` can be used for C++ and will correctly refer to the C++ source, but it will use the encoded names found in the object code. This can be avoided by employing a routine that "reverses" the encoding, that is, reads an encoded name and extracts information from it.[1] The encoding scheme is described under "The Function Name Encoding Scheme." A standard C++ name decoder should be generally available for use by debugger writers and others who deal directly with object code. Until such decoders are in widespread use the programmer must have at least a minimal understanding of the encoding scheme.

Upgrading Existing C++ Programs

Decorating the standard header files with the appropriate linkage specifications had two effects. The first phenomenon observed was that most of the declarations scattered in the program text that were referring to C functions were either redundant (because the function had already been declared in a header) or at least potentially incorrect (because they differed from the declaration of that header file on some commonly used system). The second phenomenon observed was that every non-trivial program converted to the new linkage system contained inconsistent function declarations. A noticeable number of declarations found in the program text were plain wrong, that is, different from the ones used in the function definition. This was caused in part by sloppiness, for example, where a programmer had declared a function

```
f(int ...);
```

to shut up the compiler instead of looking up the type of the second argument. A more common problem was that the "standard" header files had changed since the function declaration was placed in the text so that the "local" declaration didn't match any more; this often happens when a file is transferred from one system to another, say from a BSD to a System V.

In summary, introducing the new linkage system involved adding linkage specifications. Typically, these linkage specifications were only needed in standard header files. The process of introducing linkage specifications invariably revealed errors in the programs — even in programs that had been considered correct for years. The process strongly resembles trying `lint` on an old C program.

As was expected, some programmers first tried to get around the requirements for explicit C linkage by enclosing their entire program in a linkage directive. This might have been considered a fine way of converting old C++ programs with minimum effort had it not had the effect of ensuring that every program that uses facilities provided by such a program would also have to use the unsafe C linkage. To achieve the benefits from the new linkage scheme most C++ programs must use it. The requirement that at most one of a set of overloaded functions can have C linkage defeats this way of converting programs. The slightly slower and more involved method of using standard header files (already containing the necessary linkage specifications) and adding a few extra linkage specifications in local headers where needed must be used. This also has the benefit of unearthing unexpected errors.

Details

The scope of C function declarations has always been a subject for debate. In the context of C++ with linkage specifications and overloaded functions it seems prudent to answer some variations of the standard questions.

Default Linkage

Consider:

```
extern "C" {
        int f(int);
}


int f(int);         // default: f() has C++ linkage
```

Is it the same `f()` that was defined with C linkage above and does it have C or C++ linkage? It is the same `f()` and it does (still) have C linkage. The first linkage specification "wins" provided the second declaration has "only" default (that is, C++) linkage.

Where linkage is explicitly specified for a function, that specification must agree with any previous linkage. For example:

```
extern "C" {
        int f(int);         // f() has C linkage
}

int g();                    // default: g() has C++ linkage


extern "C++" {
        int f(int);         // error: inconsistent linkage specification
        int g();            // fine
}
```

The reason to require agreement of explicit linkage specifications is to avoid unnecessary order dependencies. The reason to allow a second declaration with implicit C++ linkage to take on the linkage from a previous explicit linkage specification is to cope with the common case where a declaration occurs both in a `.c` file and in a standard header file.

Declarations in Different Scopes

Consider:

```
extern "C" {
        int f(int);
}


void g1()
{
        int f(int);
        f(1);
}
```

Is the `f()` declared local to `g1` the same as the global `f()` and does the function called in `g1()` have C linkage? It is the same `f()` and it does have C linkage.

Consider:

```
extern "C" {
        int f(int);
}


void g2()
{
        int f(char*);
        f(1);
        f("asdf");
}
```

Does the local declaration of `f()` overload the global `f()` or does it hide it? In other words, is the call `f(1)` legal? That call is an error because the local declaration introduces a new `f()`. In the tradition of C, the declaration of `f(char*)` also draws an warning.

Consider:

```
void g3()
{
        int ff(int);
};

void g4()
{
        int ff(char*);
        ff("asdf");
        ff(1);
};
```

Does the second declaration of `ff()` overload the first? In other words, is the call `ff(1)` legal? The call is an error and a warning is issued about the two declarations of `ff()` because (as in the example above) overloading in different scopes is considered a likely mistake.

Local Linkage Specification

Linkage specifications are *not* allowed inside function definitions. For example:

```
void g5()
{
        extern "C" {            // error: linkage specification in function
                int h();
        }
}
```

The reason for this restriction is to discourage the use of local declarations of C functions and to simplify the language rules.

Alternative Solutions

So, the linkage specification scheme works, but isn't there a better way of achieving the benefits of that scheme? Several schemes were considered. This section presents the first two or three alternatives people usually come up with and explains why we rejected them. Naturally, we also considered more and weirder solutions, but all the plausible ones were variations of the ones presented here.

The Scope Trick

The first attempt to provide type-safe linkage involved the use of `overload` and the C++ scope rules. All overloaded function names were encoded, but non-overloaded function names were not. This scheme had the benefit that the linkage rules for most functions were the C linkage rules — and had the problem that those rules are unsafe. The most obvious problem was that at first glance there is no way of linking an overloaded function to a standard C library function. This problem was handled using a "scope trick":

```
overload sqrt;
complex sqrt(complex);
inline double sqrt(double d)
{
        extern double sqrt(double);    // A completely new sqrt()
                                       // not overloaded

        return sqrt(d);                // not a recursive call
                                       // but a call of the C function
                                       // sqrt
}
```

In effect, we provided a C++ calling stub for the C function `sqrt()`. The snag is that having thus *defined* `sqrt(double)` in a standard header a user cannot provide an alternative to the standard version. The problems with library combination in the presence of `overload` are not addressed in this scheme, and are actually made worse by the proliferation of definitions of overloaded functions in header files. In particular, if two "standard" libraries each overload a function then these two libraries cannot be used together since that function will be defined twice: once in each of the two standard headers.

There is also a compile time overhead involved. In retrospect, I consider this scheme somewhat worse than the original "the first overloaded has C linkage" scheme.

C "Storage Class"

It is clear that the definitions providing a calling stub are redundant. We could simply provide a way of stating that a member of a set of overloaded functions should be a C function. For example:

```
complex sqrt(complex);
cdecl double sqrt(double);      // sqrt(double) has C linkage
```

This is equivalent to

```
complex sqrt(complex);
extern "C" {
        double sqrt(double);
}
```

but less ugly. However, it involves complicating the C++ language with yet another keyword. Functions from other languages will have to be called too and they each have separate requirements for linkage so the logical development of this idea would eventually make `ada`, `fortran`, `lisp`, `pascal`, etc., keywords. Using a keyword also requires modification of the declarations of the C functions and those are exactly the declarations we would want *not* to touch since they will typically live in header files shared with an ANSI C compiler. In some cases we would even like not to touch a file in which such declarations reside.

Overload "Storage Class"

The use of a keyword to indicate that a function is a C function is logically very similar to the linkage specification solution, though inferior in detail. An alternative is to have a keyword indicate that a function should have its signature added. The keyword `overload` might be used. For example:

```
overload complex sqrt(complex);  // use C++ linkage
double sqrt(double);             // C linkage by default
```

This has the disadvantage that the programmer has to add information to gain type safety rather than having it as default and would de facto ensure that the C++ type-safe linkage rules would only be used for overloaded functions. Furthermore, this would mean that libraries could only be combined if the designers of these libraries had decorated all the relevant functions with `overload`. This scheme also invalidates all old C++ programs without providing significant benefits.

Calling Stubs

One way of dealing with C linkage would be *not* to provide any facilities for it in the C++ language, but to require every function called to be a C++ function. To achieve this one would simply re-compile all libraries and have one version for C and another for C++. This is a lot of work, a lot of waste, and not feasible in general. In the cases where recompilation of a C program as a C++ program is not a reasonable proposition (because you don't have the source, because you cannot get the program to compile, because you don't have the time, because you don't have the file space to hold the result, etc.) you can provide a small dummy C++ function to call the C function. Such a function would be written in C (for portability) or in assembler (for efficiency). For example:

```
double sqrt__Fd(d) double d; /* C calling stub for sqrt(double): */
{
        extern double sqrt();
        return sqrt(d);
}
```

A program can be provided to read the linker output and produce the required stubs.

This scheme has the advantage that the user works in what appears to be an "all C++" environment (but so does the adopted scheme once a few C libraries have been recompiled with C++ and/or a few header files have been decorated with linkage specifications). It does, however, also suffer from a few severe disadvantages. A "C calling stub maker" program cannot be written portably. Therefore, it would become a bottleneck for porting C++ implementations and C++ programs and thus a bottleneck for the use of C++. It is also not clear that this approach can be implemented everywhere without loss of efficiency since it requires large numbers of functions to have two names (a C name and a C++ name). This takes up code space and introduces large numbers of extra names that would slow down programs reading object files such as linkers, loaders, debuggers, etc. The C calling interfaces would also be ubiquitous and available for anyone to use by mistake, thus re-introducing the C linkage problems in a new guise.

Encode Only C++ Functions

The fundamental problem with all but the last scheme outlined above is that they require the programmer to decorate the source code with directives to help the compiler determine which functions are C functions. Ideally, the compiler would simply look at the program and determine the linkage necessary for each individual function based on its type. Could the compiler be that smart? Unfortunately, no. There is no way for the compiler to know whether

```
extern double sqrt(double);
```

is written in C or C++. However, one might handle most cases by the heuristic that if a function is clearly a C++ function it gets C++ linkage and if it isn't it gets C linkage. For example:

```
complex sqrt(complex);          // clearly C++: sqrt__F7complex
double sqrt(double);            // could be C:sqrt
```

Since `complex` is a class, `sqrt(complex)` is clearly a C++ function and it is encoded. The other `sqrt()` might be C so it isn't.

Applying this heuristic would mean that most functions would not have type-safe linkage — but we are used to that. It would also mean that overloading a function based on two C types would be impossible or require special syntax:

```
int max(int,int);
double max(double,double);
```

Such overloading *must* be possible because there are many such examples and several of those are important, especially when support for both single and double precision floating point arithmetic becomes widespread:

```
float sqrt(float);
double sqrt(double);
```

This implies that either `overload` or linkage specifications must be introduced to handle such cases. The heuristic nature of the specification of where these directives are needed will lead to confusion, overuse, and errors.

If `overload` is re-introduced, the cautious programmer will use it systematically wherever a relatively simple class is used (in case a revision of the system should turn it into a plain C struct), wherever an argument is typedef'd (because that `typedef` might some day refer to a plain C type), and wherever there is any doubt. This will lead to the now well known problems of combining libraries. Similarly, if linkage specifications are required anywhere, they will proliferate because of doubts about where they are needed.

It does not seem wise to refrain from checking linkage in a large number of cases and to introduce a rather arbitrary heuristic into the linking rules for C++ without being able to reduce the complexity of the language or to reduce the burden on the programmer somewhere.

Nothing

Naturally, while considering these alternative schemes the easy option of doing nothing was regularly reconsidered. However, the original scheme still suffers from the problems described in section 3: insecure linkage, spurious `overload` declarations, and overloading rules that complicate the life of library writers and library users.

Syntax Alternatives

The scheme of giving all C++ functions type-safe linkage and providing a syntax for expressing that a given function is to have C linkage was thus chosen and tried. However, there were still several alternatives for expressing C linkage for this general scheme.

Why `extern`?

Instead of employing the existing keyword `extern` we might have introduced a new one such as `linkage` or `foreign`. The introduction of a new keyword always breaks some programs (though usually not in any serious way and for a well chosen new keyword not many programs) and `extern` already has the right meaning in C and C++. In almost all cases `extern` is redundant since external linkage is the default for global names and for locally declared functions. When used, `extern` simply emphasizes the fact that a name should have external linkage. The use of `extern` introduced here merely allows the programmer to tag an `extern` declaration with information of *how* that linkage is to be established.

Linkage for Individual Functions

One obvious alternative is to add the linkage specification to each individual function:

```
    extern "C" double sqrt(double);  // sqrt(double) has C linkage
```

The problem with this is that it does not serve the need to be able to give a set of C functions C linkage with one declaration and requires the declaration of every C function to be modified. In particular, it does not allow a C header (that is, an ANSI C header) to be used from a C++ program in such a way that all the functions declared in it get C linkage.

This notation for linkage specification of individual functions is not just an alternative to the linkage "block" adopted but also an obvious extension to the adopted syntax. I intend to review the situation after the current scheme has been used a while longer to see if the use of linkage specifications warrants this extension.

Linkage Pragmas

The original implementation of the linkage specifications used a `#pragma` syntax:

```
#pragma linkage C
double sqrt(double);        // sqrt(double) has C linkage
#pragma linkage
```

This was considered too ugly by many but did appear to have significant advantages. For example, it can be argued that linkage to "foreign languages" is not part of the language proper. Such linkage cannot be specified once and for all in a language manual since it involves the *implementations* of *two* languages on a given system. Such implementation specific concepts are exactly what pragmas were introduced into Ada and ANSI C to handle. The `#pragma` syntax was trivial to implement and easy to read. It was also ugly enough to discourage overuse and to encourage hiding of linkage specifications in header files.

There are problems with this view, though. For example, it is most often assumed that any `#pragma` can be ignored without affecting the meaning of a program. This would not be the case with linkage pragmas. Another problem is that for the moment many C implementations do not support a pragma mechanism and it is not certain that those that do can be relied upon to "do the right thing" for linkage pragmas used by a C++ compiler.

Linkage to a particular foreign language does not belong in C++ because such linkage will in principle be local to a given system and non-portable. However, the fact that linkage to other languages occurs is a general concept that can and ought to be supported by a language intended to be used in multi-language environments. In practice, one can assume that at least C and Fortran will be available on most systems where C++ is used and that a large group of users will need to call functions written in these languages. Consequently, one would expect C++ implementations to support C and Fortran linkage.

The fact that C (like most other languages) does not provide a concept of linkage to program fragments written in other languages led to the absence of an explicit linkage mechanism in C++ and to the problems of link safety and overloading.

Special Linkage Blocks

Another approach would be to introduce a new keyword, say `linkage`, and use it to specify both the start and the end of a linkage block:

```
linkage("C");
double sqrt(double);        // sqrt(double) has C linkage
linkage("");
```

This avoids introducing yet another meaning for `{}`, allows setting and restoring of linkage to be two separate operations, allows all linkage directives to be found by simple pattern matching in a line oriented editor, and allows all linkage directives to be suppressed by a single macro

```
#define linkage(a)
```

The problem with this seems to be that it tempts people to think of linkage as a compiler "mode" that can be switched on and off at random times and doesn't obey block structure. For example:

```
linkage("C");

double sqrt(double);            // sqrt(double) has C linkage

f() {
        extern g();             // g() has C linkage
linkage("");
        extern h();             // h() has C++ linkage
        ...
}
```

It also becomes hard to convince people that linkage specifications come in pairs and can be nested.

The same approach, with the same educational problems, can be tried without introducing a new keyword:

```
extern "C";
double sqrt(double);      // sqrt(double) has C linkage
extern "";
```

Note that whatever syntax was chosen, linkage specifications were intended to obey block structure to be fit cleanly into the language. In particular, if linkage "blocks" and ordinary blocks were not obliged to nest the job of writers of tools manipulating C++ source text, such as a C++ incremental compilation environment, would be needlessly complicated.

Conclusions

The use of function name encodings involving type signatures provides a significant improvement in link safety compared to C and earlier C++ implementations. It enables the (eventual) abolition of the redundant keyword `overload` and allows libraries to be combined more freely than before. The use of linkage specifications enables relatively painless linkage to C and eventually to other languages as well. The scheme described here appears to be better than any alternative we have been able to devise.

The Function Name Encoding Scheme

The (revised) C++ function name encoding scheme was originally designed primarily to allow the function and class names to be reliably extracted from encoded class member names. It was then modified for use for *all* C++ functions and to ensure that relatively short encodings (less than 31 characters) could be achieved reliably for systems with limitations on the length of identifiers seen by the linker. The description here is just intended to give an idea of the technique used, not as a guide for implementors.

The basic approach is to append a function's signature to the function name. The separator __ is used so a decoder could be confused by a name that contained __ except as an initial sequence, so don't use names such as a__b__c in a C++ program if you like your debugger and other tools to be able to decompose the generated names.

The encoding scheme is designed so that it is easy to determine

- if a name is an encoded name
- what (unencoded) name the user wrote
- what class (if any) the function is a member of
- what are the types of the function arguments

The basic types are encoded as

`void`	`v`
`char`	`c`
`short`	`s`
`int`	`i`
`long`	`l`
`float`	`f`
`double`	`d`
`long double`	`r`
`...`	`e`

A global function name is encoded by appending `__F` followed by the signature so that `f(int,char,double)` becomes `f__Ficd`. Since `f()` is equivalent to `f(void)` it becomes `f__Fv`.

Names of classes are encoded as the length of the name followed by the name itself to avoid terminators. For example, `x::f()` becomes `f__1xFv` and `rec::update(int)` becomes `update__3recFi`.

Type modifiers are encoded as

`unsigned`	`U`
`const`	`C`
`volatile`	`V`
`signed`	`S`

so `f(unsigned)` becomes `f__FUi`. If more than one modifier is used they will appear in alphabetical order so `f(const signed char)` becomes `f__FCSc`.

The standard modifiers are encoded as

`pointer *`	`P`
`reference`	`&R`
`array`	`[10]A10_`
`function()`	`F`
`ptr to member`	`S::*M1S`

So `f(char*)` becomes `f__FPc` and `printf(const char* ...)` becomes `printf__FPCce`.

To shorten encodings repeated types in an argument list are not repeated in full; rather, a reference to the first occurrence of the type in the argument list is used. For example:

```
f(complex,complex);            // f__F7complexT1
                               // the second argument is of the same
                               // type as argument 1

f(record,record,record,record);// f__F6recordN31
                               // the 3 arguments 2, 3, and 4 are of
                               // the same type as argument 1
```

A slightly different encoding is used on systems without case distinction in linker names. On systems where the linker imposes a restriction on the length of identifiers, the last two characters in the longest legal name are replaced with a hash code for the remaining characters. For example, if a 45 character name is generated on a system with a 31 character limit, the last 16 characters are replaced by a 2 character hash code yielding a 31 character name.

Naturally, the encoding of signatures into identifier of limited length cannot be perfect since information is destroyed. However, experience shows that even truncation at 31 characters for the old and less dense encoding was sufficient to generate distinct names in real programs. Furthermore, one can often rely on the linker to detect accidental name clashes caused by the hash coding. The chance of an undetected error is orders of magnitude less than the occurrence of known problems such as C programmers accidentally choosing identical names for different objects in such a way that the problem isn't detected by the compiler or the linker.

Footnotes

1. Naturally, this would be the same function as was used to write the linker output filter. The examples here are based on the name decoding routine written by Steve Brandt and used to modify the UNIX System V C debugger `sdb` into `sdb++`.

10 Access Rules for C++

Access Rules for C++

NOTE

This chapter is taken directly from a paper by Phil Brown.

Introduction

One feature of C++ is the provision for function and data protection through a combination of the following:

- `public`, `protected`, and `private` class members

  Every class member has an associated level of protection. `public` indicates no protection, whereas `private` indicates access is limited to members and friends. `protected` is similar to `private` except that it allows access additionally to derived classes.

- inheritance

  Derived classes are defined in terms of base classes. Inheritance is the name and description of this process, by which a derived class acquires the data and functions of its base classes. As previously noted, the `private` members of the base classes are not accessible in the derived class. The protection of other members is dependent on the type of the derivation. `public` and `protected` members of `public` base classes will have the same protection in the derived class. These same members from a `private` base class will be `private` in the derived class. (See Figure 10-1)

- friendship

  Friendship overrides all protections within a class. A friend declaration within a class denotes another class[1] or function as a *potential* friend.

The following access rules define when a *potential* friend will be considered a friend.

This paper defines the C++ access rules, as they relate to the various protection methods, and explains some of the reasoning for these rules.

Access Rules

1. Any visible non–"class member" is accessible.
2. If an object is accessible, then

   a. `public` members of the object's class type are accessible.

   b. *potential* friends of the object's class type will be considered friends.

c. The same level of access applies to the `public` base classes of the object's class type.

3. All members of a class, and `public` and `protected` members of its base classes, are accessible by member and friend functions of the class.[2]

Explanation

1. *Any visible non-"class member" is accessible.*

   The first of the access rules is the starting point for many references. In the following:

```
int i;

void
f() {
        i = 1;          // OK - Rule #1
}
```

   the variable `i` is accessible since it is not a class member and is visible in the function `f`.

2. *If an object is accessible, then*

a. `public` *members of the object's class type are accessible.*

   The first part of the second rule is a restatement of its condition. Access to `public` members of a class object is the minimal amount of accessibility (excluding *no access*).

```
class B {
public:
        int i;
};

void
f() {
        B b;
        b.i = 1;        // OK - Rule #1, #2a
}
```

   In this case, the variable `b` is accessible by Rule #1. Since `b` is accessible, the `public` member `i` of `class B` will be accessible (Rule #2a).

b. potential *friends of the object's class type will be considered friends.*

   One way to view this is to consider a friend declaration as a `public` member which will not be honored unless that friend declaration is accessible. Once friendship *has* been established, access is described by Rule #3.

```
class B {
private:          // unnecessary
        int i;
        friend void f();
};

class D : private B {
};

void
f() {
        B b;
        b.i = 1; // OK - Rule #1, #2b, #3
        D d;
        d.i = 1; // ERROR - Rule #1, #2a, -fail-
}
```

In this example, both variables `b` and `d` are accessible according to Rule #1. However, in the first case, the function `f` is a friend of `class B` since, by Rule #2b, `b` is accessible and `class B` has a friend declaration for the function `f`. Rule #3 states that, as a friend, `f` will have access to all of the members of `class B`. The assignment to `b.i` is thus valid. In the second case, the `public` members of `d` are accessible according to Rule #2a. Since function `f` is not a friend of `class D`, and `class B` is not a `public` base class of `class D`, there are no other access rules to apply. The assignment to `d.i` is invalid.

c. *the same level of access applies to the* `public` *base* classes of the object's class type.

This rule applies when Rule #3 cannot (access is not by a member or friend). Notice that there will be *no access* to `private` base classes.

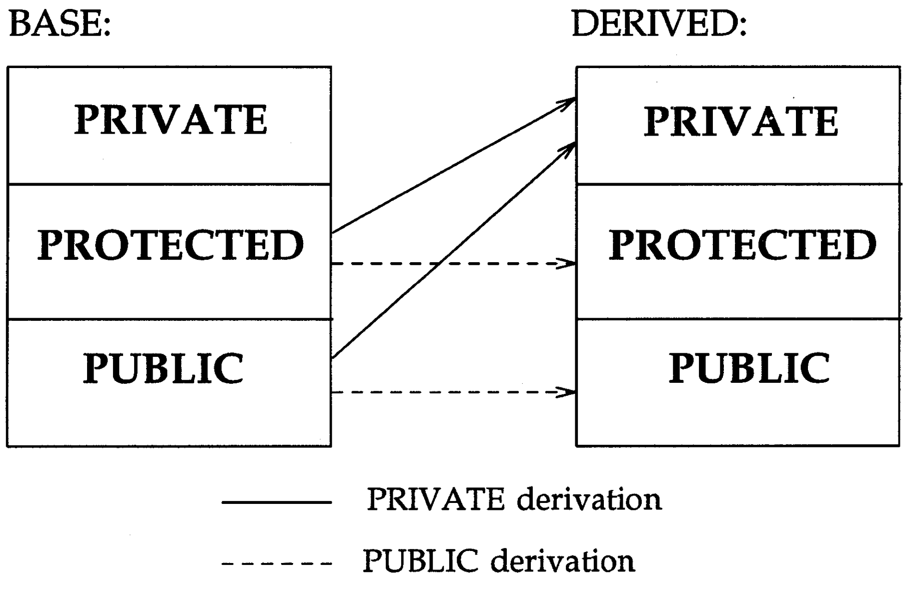
```
class B {
public:
int i;
};

class D : public B {
private:                    // unnecessary
int j;
};

void
f() {
D d;
d.i = 1;                    // OK - Rule #1, #2a, #2c
d.j = 1;                    // ERROR - Rule #1, #2a, -fail-
}
```

In this example, the variable `d` is accessible according to Rule #1. According to Rule #2a, the `public` members of `class D` are thus accessible. Since `j` is a `private` member of `class D`, it will not be accessible. However, by Rule #2c, since `class B` is a `public` base class of `class D`, the `public` members of `class B` will also be accessible. The assignment to `d.i` is valid.

3. *All members of a class, and* `public` *and* `protected` *members of its base classes, are accessible by member and friend functions of the class.* (self-explanatory)

The reasoning for the rules as they apply to inheritance is illustrated by Figure 10-1.

Figure 10-1: Derivation Relationship



This diagram shows the level of protection of a base class member when referenced through a derived class. As indicated in Rule #3, since friends and members of the derived class have access to all members of the derived class, they will also have access to the `public` and `protected` members of any base class.

When neither a friend nor member of the derived class, access to base class members will be determined by the type of derivation. If it is a `private` derivation, the base class members will be `private` in the derived class. As such, the base class members will not be accessible. However, in a `public` derivation, the same level of access will apply for base class members as applies within the derived class.

Base Member Declarations

`public` and `protected` base member declarations in a derived class (of the form `base_class::member`) can be used to alter the accessibility of class members. When given in a `private` derived class, a base member declaration will make the designated base member appear to be a member of the derived class.[3] Thus, accessibility of the member will be determined at the level of the derived class.

A superfluous base member declaration (i.e., one given in a `public` derived class) is ignored. This is necessary since an inaccessible base member declaration can conceivably hide a validly accessible base member.

```
class A {
protected:
        int i;
        friend f();
};

class B : public A {
protected:
        A::i;
};

void f() {
        B* p;
        p->i = 1;                   // This would be illegal if the base
                                    // member declaration was not ignored
}
```

Examples (Not Interdependent)

```
//------ start of example 01 ------

class B {
        int i;
        friend void f();
};

class D : public B {
};

void
f() {
        B* p = new B;
        D* q = new D;

        int fi1 = p->i;         // OK - Rule #1, #2b, #3
        int fi2 = q->i;         // OK - Rule #1, #2a, #2c, #2b, #3
}

//------ start of example 02 ------

class B {
        int i;
};

class D : public B {
};

void
f() {
        B* p = new B;
        D* q = new D;

        int fi1 = p->i;         // ERROR - Rule #1, #2a, -fail-
        int fi2 = q->i;         // ERROR - Rule #1, #2a, #2c, -fail-
}

//------ start of example 03 ------

class B {
        int i;
        friend C;
};
```

```
class C : private B {
         friend D;
         void f1() {
         int fi1 = i;           // OK - Rule #3, #2b, #3
         }
};

class D : public C {
         void f2() {
         int fi2 = i;           // ERROR - Rule #3, #2b, #3, -fail-
         }
};

//------ start of example 04 ------

class B {
         int i;
         friend D;
};

class C : private B {
};

class D : public C {
         void f() {
         int fi1 = i;           // ERROR - Rule #3, -fail-
         }
};

//------ start of example 05 ------

class B {
         int i;
         friend D;
};

class C : public B {
};

class D : private C {
         void f() {
         int fi1 = i;           // OK - Rule #3, #2c, #2b, #3
         }
};

//------ start of example 06 ------
```

```
class B {
        int i;
        friend D;
};

class D {
        void f() {
        B* p = new B;
        int fi1 = p->i;         // OK - Rule #1, #2b, #3
        }
};

//------ start of example 07 ------

class B {
protected:
        int a;
};

class D : public B {
        friend void f();
public:
        int b;
};

void
f() {
        D* p;
        p->a = 1;               // OK - Rule #1, #2b, #3
        p->b = 2;               // OK - Rule #1, #2a

        B* pp;
        pp->a = 1;              // ERROR - Rule #1, #2a, -fail-
        pp->b = 1;              // ERROR - Rule #1, #2a, -fail-

        pp = p;
        pp->a = 1;              // ERROR - Rule #1, #2a, -fail-
        pp->b = 2;              // ERROR - Rule #1, #2a, -fail-
}

//------ start of example 08 ------

class A {
protected:
        int a;
};
```

```
class B : public A {
};

class C : public B {
        void f(B* p);
};

void
C::f(B* p) {
        a = 1;                  // OK - Rule #3, #2c
        p->a = 2;               // ERROR - Rule #1, #2a, #2c, -fail-
}

//------ start of example 09 ------

class A {
        int a;
        friend void f();
};

class B : public A {
};

void
f() {
        B* p;
        p->a = 1;               // OK - Rule #1, #2a, #2c, #2b, #3

        A* p2;
        p2->a = 2;              // OK - Rule #1, #2b, #3
}

//------ start of example 10 ------

class B {
        friend void f1();
public:
        int a;
};

class C : private B {
        friend void f2();
};

class D : public C {
};
```

```
void
f1() {
        D* p1;
        p1->a = 1;              // ERROR - Rule #1, #2a, #2c, -fail-
}

void
f2() {
        D* p2;
        p2->a = 1;              // OK - Rule #1, #2a, #2c, #2b, #3
}

//------ start of example 11 ------

class B {
        friend void f1();
        int a;
};

class C : private B {
        friend void f2();
};

class D : public C {
};

void
f1() {
        D* p1;
        p1->a = 1;              // ERROR - Rule #1, #2a, #2c, -fail-
}

void
f2() {
        D* p2;
        p2->a = 1;              // ERROR - Rule #1, #2a, #2c, #2b, #3, -fail-
}

//------ start of example 12 ------

class B {
        friend void f1();
public:
        int a;
};
```

```
class C : public B {
        friend void f2();
};

class D : public C {
};

void
f1() {
        D* p1;
        p1->a = 1;              // OK - Rule #1, #2a, #2c, #2c
}

void
f2() {
        D* p2;
        p2->a = 1;              // OK - Rule #1, #2a, #2c, #2b, #3
}

//------ start of example 13 ------

class B {
        friend void f1();
        int a;
};

class C : public B {
        friend void f2();
};

class D : public C {
};

void
f1() {
        D* p1;
        p1->a = 1;              // OK - Rule #1, #2a, #2c, #2c, #2b, #3
}

void
f2() {
        D* p2;
        p2->a = 1;              // ERROR - Rule #1, #2a, #2c, #2b, #3, -fail-
}

//--------------------------------
```

Footnotes

1. Denoting a class as a friend, in effect, denotes each function member of that class as a friend.
2. Rules #2b and #3 can be combined to override Rule #2c.
3. A `public` base member declaration must appear in a `public` section of the derived class. Similar logic applies to the `protected` case.

11 Inline Functions in C++

Inline Functions in C++

NOTE This chapter is taken directly from a paper by Dennis Mancl.

Abstract

Inline functions in C++ permit the programmer to increase the execution time efficiency of a program. There are some places, however, where inline functions should not be used — for functions that the compiler is incapable of expanding inline.

Introduction

Inline functions are a useful feature in the C++ programming language. When they are used judiciously, the run-time efficiency of the programs where they are used can be improved considerably. But not all uses of inline functions will cause programs to run faster. The purpose of this chapter is to describe the proper use of C++ inline functions and to point out some of the pitfalls in their use.

This paper discusses the implementation of inline functions in the AT&T C++ Language System Release 2.1. Other C++ compilation systems exist, and these have subtle differences with the information presented here.

Regular Inline Functions

C++ functions are declared inline by putting the keyword `inline` before the definition of the function. For example:

```
// example program inline1.c:

inline int min(int a, int b)
{
        return ((a < b) ? a : b);
}
```

Inline functions increase the execution speed of a program by getting rid of the normal subroutine call overhead. In a program calling a normal function, the actual code for the function is generated by the compiler in one place, with a return from subroutine instruction at the end. Each call to the function is translated into instructions that place the function arguments on the stack, place the return address on the stack, jump to the start of the subroutine, and clean up the stack after the return.

Inline functions improve execution speed by eliminating the steps of stacking the arguments, jumping to the subroutine, and cleaning up the stack. Instead, the function's code is repeated in each place where the function is called. This may create a very large program if an inline function is large and is called in many places in a program — the use of inline functions is a space-time tradeoff. The inline function feature is used most often for very simple functions.

In order to make a clearcut decision on whether a function should be inline or not, five pieces of information must be estimated:

1. the object code size of the function
2. the object code size of the stacking, jumping, and cleanup code
3. the execution time of the stacking, jumping, and cleanup code
4. the number of places in the program where the function is called
5. the average number of times the function is actually executed in a single run of the program

Item 1 can be determined easily by compiling the function separately. Items 2 and 3 are more difficult to determine — it is necessary to look at the assembly code generated by the C compiler. Item 4 can be counted directly from the code, and item 5 can be found by running the program with a profiler such as `prof`, `lprof`, or `gprof`. With this information, the cost in space and the benefit in time can be determined. (Space cost = [(1) - (2)] * (4), time savings = (3) * (5). Notice that for very small functions, the space cost can be negative, that is, certain inline functions save both time and space.) In real life this kind of formal analysis is rarely performed — but programmers use their own intuitive estimates of these quantities to decide where `inline` should be used.

Many normal functions can be made into inline functions. According to the definition of the C++ `inline` keyword, `inline` is treated as a "hint" to the compiler — the compiler may choose to ignore the hint. See the *AT&T C++ Language System Release 2.1 Product Reference Manual*, page 36, for details about the `inline` keyword. In the AT&T C++ Language System some circumstances prevent inline expansion — for instance, loops are not allowed in an inline function. A more complete (but not totally exhaustive) list of the translator's expansion rules for inline functions appears below. In some cases where the translator can't expand a function, it produces an error message and the function must be rewritten. In other cases, the translator gives a warning message indicating that the function will not be expanded inline, but the function will be converted to a static function — this means that no execution speed improvement will occur and there may be a possible program size penalty if the inline function is included in multiple source files. Finally, there are cases where the translator produces no warning message, but a static copy of the inline function is added to the object file.

Inline Member Functions

There are two different ways of defining C++ inline functions that are member functions of a class. The first and most common way is to include the definition of the function in the declaration of the class. In this kind of inline function definition, the keyword `inline` is optional.

```
// example program inline2.c:

class example {
      int hrs;
      int mins;
public:
      void settime(int hval, int mval) { hrs = hval; mins = minval; }
};
```

The second way uses the `inline` keyword before the definition of a member function outside of the class declaration.

```
// example program inline3.c:

class example {
        int hrs;
        int mins;
public:
        int seconds_after_midnight();
};
inline int example::seconds_after_midnight() {
        return (60 * (mins + 60*hrs));
}
```

Both methods of defining inline member functions are okay, but the second is very useful in the case when it is necessary to relocate the definition of an inline function to another part of the file in order to eliminate forward references to other inline functions. (But the function definition can't be moved from the `.h` file containing the definition of the class to a single `.c` file, because all modules using the function must contain the definition of the function.)

Inline Constructors and Destructors

Constructors and destructors can also be inline functions. Inline constructors or destructors cause the space-time tradeoff analysis to be more complicated — for two reasons. First, it is more difficult to count the number of places in the program where a constructor or a destructor is called than to count the number of calls to a normal function. Constructor functions are called for declarations, conversions, and invocations of the `new` operator, and destructor function calls are at the end of a block that contains a declaration of a class object or where the `delete` operator is invoked. Second, the code generated by an inline constructor or destructor function in a derived class will contain the code from the inline constructor or destructor in the base class, if the corresponding base class constructor or destructor is also an inline function.

Inline constructors and destructors are very useful in reducing the execution time for initialization and cleanup of class objects. Estimating the cost in space is easier to do by experimentation than by analysis.

Examples of Inline Function Errors and Warnings

When an inline function is declared, it is not always possible to do an inline expansion of the function. An inline function that cannot be expanded is converted to a "static" function — a normal non-inline function whose scope is limited to the `.c` file in which it is contained.

If an inline function cannot be expanded, as is the case in some of the examples below, the function can have a large negative impact on the amount of space used by a program. Most inline function definitions are found in header files (`.h` files) which define variables and function prototypes for many different parts of a larger C++ program. In the compilation process, the C++ compilation system will put a duplicate static copy of the inline function in many different object files.

In an extreme case, in a C++ program that consists of 100 `.c` files, each of which `#includes` the header file defining an inline function, there is a possibility that 100 static copies of the inline function may appear in the final executable file. In a couple of the examples given below (example programs `inline9.c` and `inline11.c`), a static copy of an inline function is produced even though there is no inline function invoked in the program. These "non-inline inline" constructs should be avoided.

The following is a list of some examples where inline functions are converted to static functions.

- An inline function definition contains a loop.

```
// example program inline4.c:

inline char *find_next(char *string, char objective)
{
    while (*string && (*string != objective)) string++;
    return ((*string == objective) ? string : NULL);
}
```

  In this case, the translator will produce the following warning message (in C++ Release 2.1, only if the `+w` option is used).

```
warning: "inline" ignored,  find_next() contains loop
```

  It will proceed to generate code — in this case, the function is converted to a static function.

- An inline function contains multiple returns.

```
// example program inline5.c:

#include <string.h>
inline char *my_strcpy(char *dest, char *src)
{
      if (dest == 0) return (0);
      return (strcpy(dest, src));
}
```

This program causes a translator error message:

```
sorry, not implemented: cannot expand inline
function my_strcpy() with statement after "return"
```

This problem can be sidestepped by making a single return.

```
// example program inline6.c:

#include <string.h>
inline char *my_strcpy(char *dest, char *src)
{
        char *retval;
        if (dest == 0) retval = 0;
        else retval = strcpy(dest, src);
        return (retval);
}
```

- An inline function contains a local array variable.

```
// example program inline7.c:

#include <string.h>
inline void basename(char *filename) {
        char basename_buf[15];
        char *p;
        if ((p = strrchr(filename, '/')) != 0) {
                strncpy(basename_buf, p + 1, 15);
                basename_buf[14] = '\0';
                strcpy(filename, basename_buf);
        }
}
```

This program causes a translator error message:

```
sorry, not implemented: cannot expand inline function
needing temporary variable of vector type
```

at the place where the inline function is called. A similar message would be produced if the local array were declared `static char basename_buf[15]`. In order to make this function work, the array needs to be made static and it must be moved outside of the function definition.

- An inline function is defined recursively.

```
// example program inline8.c:

inline int factorial(int n) {
        return ((n == 0) ? 1 : (n * factorial(n - 1)));
}
```

This example compiles with no warning messages from the translator (unless the +w option is used). In fact, any call to this function is expanded inline, but the recursive call within the function definition is not expanded. For example, the statements

```
int n = 5;
m = factorial(n);
```

are translated into

```
int n = 5;
m = ((n == 0) ? 1 : (n * factorial(n - 1)));
```

- There are nested calls to an inline function in another inline function.

```
// example program inline9.c:

inline int min(int a, int b)
{
        return ((a < b) ? a : b);
}

inline int min3(int a, int b, int c)
{
        return (min(a, min(b, c)));        // An inline function that
                                           // makes nested calls to another
                                           // inline function
}
```

In this example, the function `min()` becomes a static function. This occurs even if there is no call to the `min3()` function anywhere in the program. The translator only gives a warning message to indicate that a static copy of `min()` has been created if the +w option is present.

The translator will only expand an inline function once in an expression. This can be sidestepped by splitting this into two expressions:

```
// example program inline10.c:

inline int min3(int a, int b, int c)
{
        int temp = min(b, c);           // this works okay -- no static
        return (min(a, temp));          // copy of min() is created
}
```

- An inline function is called by a previously defined inline function.

  This case can only happen within a class definition, because in any other case, the compiler gives an error message for a forward reference from an inline function to another inline function.

```
// example program inline11.c:

class example {
        int hrs;
        int mins;
public:
        void roundup() { clearmins(); hrs++; };
                // roundup() contains a forward reference
                // to the inline function clearmins()
        void clearmins() { mins = 0; }
};
```

  The function `clearmins()` is called before it is defined. In this example, the function `clearmins()` becomes a static function. This occurs even if there is no call to the `roundup()` function anywhere in the program. The translator gives a warning message to indicate that a static copy of `clearmins()` has been created only if the `+w` option is present.

  This problem can be sidestepped by changing the order of the definitions of the functions `roundup()` and `clearmins()`.

- The address of an inline function is needed.

```
// example program inline12.c:

inline int min(int a, int b)
{
        return ((a < b) ? a : b);
}
extern void do_function(int (*)(int, int));

main() {
        do_function(&min);
}
```

A static copy of the inline function is added to the file so that the function pointer can point to a real function. Normal calls to the `min()` function are expanded inline — only calls through the function pointer will call the static copy of the function.

This program and the next two are examples of the static copy of the inline function being triggered by the use of the function rather than by the definition of the function.

- An inline function is also virtual.

  This is a result of the implementation of virtual functions. The virtual function table must have a pointer to an actual function, so a static copy of the function is created. The static copy of the function is usually added to only one file — that's the file where the translator puts the virtual function table, which is usually the file that contains the definition of the first non-inline virtual function.

```
// example program inline13.c:

class baseclass {
        int data;
public:
        virtual inline void clrdata() { data = 0; };
};
main() {
        baseclass b, *baseptr;
        b.clrdata();                        // inline only in C++ 2.0 or 2.1
                                            //    (not in C++ 1.2)
        baseptr->clrdata();                 // never inline
        baseptr->baseclass::clrdata();      // always inline
}
```

The "virtual inline" function definition is sometimes useful, because of the execution speed efficiency of inline expansion in the cases where the function can be expanded inline. The choice of whether to make a virtual function into an inline virtual function is based on the same space-time tradeoffs as with normal functions, but in the analysis it is necessary to remember that function calls that use the "virtual" mechanism (as is the case in the example program above: `(baseptr->clrdata())` never get the benefit of inline expansion.

How to Find Inline Functions That Are Not Expanded

In a C++ *library*, a collection of C++ classes and functions that will be used by many programmers in many places, a simple check should be made for functions that are not expanded inline. One way to find the "non-inline" inlines is to compile the library with the +w option. This option will give warnings about all of the examples given in the previous section. Another way to find functions that are being converted to static functions by the C++ compilation system is to look at the symbol table of a test program. (The nm(1) command prints a list of the names in the symbol table of a .o file.) If the symbol table contains the names of "inline" functions, then those functions are being converted to static functions, because inline functions normally don't turn up in the symbol table.

Here's an example.

```
// example program inline14.h:

#include <memory.h>
class SimpleStr {
        char *stringbuffer;
        int length;
public:
        SimpleStr() { stringbuffer = 0; }
        SimpleStr(int str_length) {
                stringbuffer = new char[str_length];
                length = str_length;
                clrbuf();
        }
        void clrbuf() { memset(stringbuffer, 0, length); }
};
```

In order to test this code to determine if there is a "non-inline" inline function, a simple .c has to be compiled:

```
// example program inline14.c:

#include "inline14.h"
SimpleStr s;
```

The "non-inline" inline functions can be found by applying the following commands to the object file:

```
nm inline14.o | grep "static" | grep "\.text" | c++filt
```

Running this set of commands produces:

```
SimpleString::clrbuf() |  52|static|    |    |.text

C++ symbol mapping
demangled:               mangled:

SimpleString::clrbuf()    _clrbuf__12SimpleStringFv
```

A more complicated tool could be written to search the source file for inline function definitions and to search the object file symbol table for the matching function name. A more complete test program would include calling each of the inline functions.

Summary

In conclusion, the inline function construct in the C++ programming language is a useful feature. It needs to be used selectively — keeping in mind the space-time tradeoffs in using them and the places where inline definitions add no execution speed improvement to the program.

12 As Close as Possible to C — But No Closer

As Close as Possible to C — But No Closer

NOTE

This chapter is taken directly from a paper by Andrew Koenig and Bjarne Stroustrup.

Introduction

ANSI C and the C subset of C++ serve subtly different purposes.

The purpose of ANSI C is to provide a standard: to codify existing practice and resolve inconsistencies among existing implementations. The purpose of C++ is to provide C programmers with a tool they can use to shape their thinking in fundamentally different ways. Both aimed at compatibility with "Classic C" and both came close to hitting their mark.

The two goals have necessarily resulted in some fundamental differences of approach between the two languages. In a few cases, C++ departed slightly from "Classic C" – always with knowledge of the cost of doing so and always with the aim to gain something well worth that cost. X3J11 did the same according to its aims and constraints. Wherever possible, C++ has adopted the X3J11 modifications and resolutions and in a few noteworthy cases ANSI C adopted C++ features.

The purpose of this chapter is to summarize the remaining differences between the ANSI C standard and C++, explain their motivation, and point out cases where these differences are less important than they might appear at first.

Below, C refers to C as defined by the December 7, 1988 ANSI C standard and C++ refers to C++ as defined in the February 1990 draft C++ *Reference Manual*. We use the word "difference" to refer to something that is C but not C++. Things that can be done in C++ but not C are not interesting in this context unless they also somehow restrict C++ from expressing something that is C.

Note that in this context pure extensions of C provided by C++ are *not* incompatibilities.

Name Spaces and Nesting

Structure Name Spaces

C puts variables and structure tags in separate name spaces; C++ uses a single name space. The reason for this, of course, is that abstract data types – classes – are a crucial part of the foundation of C++ and it is important to be able to use them as naturally as if they were built-in types. Essentially every C++ program depends on this.

The place where it matters most – at least the place where people have complained the most – is when a library function deals with a structure with the same name. For instance:

```
struct stat {
        /* member declarations */
};
int stat(const char * , struct stat *);
```

The C++ language definition therefore has a compatibility wart to allow precisely this kind of thing. We believe this will smoothly accommodate most existing C usages while still allowing the economical expression C++ programmers have come to appreciate and depend on.

The only remaining difference between C and C++ in the name space area is that C++ does not allow a name to be declared as both a structure tag and a (different) `typedef` name in the same scope. For example:

```
struct stat {
        /* member declarations */
};
typedef int stat;
```

Allowing this construct in C++ would create serious problems with composition of header files describing libraries since declarations of functions, variables, and classes then could undetectably change meaning as the result of header file inclusions. Note that C++ specifically does allow the following common C usage:

```
typedef struct A {
        /* member declarations */
} A;
```

Structure Nesting

In both C and C++, a structure may be declared inside another:

```
struct Outer {
        int a;
        int b;
        struct Inner {
                int x;
                int y;
        } c;
        int d;
};
```

In C, this is merely a notational convenience: the declaration above is precisely equivalent to:

```
struct Inner {
        int x;
        int y;
};

struct Outer {
        int a;
        int b;
        struct Inner c;
        int d;
};
```

In C++, structures are classes, classes can have member functions, and member functions obey the same scope rules as any other functions. As a result, it is necessary for classes to obey the normal scope rules as well, so that in the first example above, the name `Inner` is only directly visible inside the body of the `Outer` class declaration and its associated member functions. For example:

```
struct Outer {
        int a;
        int b;
        struct Inner {
                int x;
                int y;
        } c;
        int d;
};

void f()
{
        Outer limits;           /* legal C and C++ */
        Inner sanctum;          /* legal C, illegal C++ */
        Outer::Inner view;      /* legal C++, illegal C */
}
```

This difference should not cause trouble in practice, because a considerate C++ implementation will detect invalid C++ usages that are valid C, issue an appropriate warning, and use the C treatment. Of course, good programming practice argues against *declaring* a name like `Inner` in a way that makes it look nested, and then *using* it in a way that requires that it be externally visible.

Similarly, the C++ notion that a class establishes a scope is useful for declaring enumerations. They are kept in the scope of their class, and accessible elsewhere – subject to access control – by explicit qualification with their class name:

```
class X {
public:
        enum state { good, bad, fail };
        state readstate();
        // ...
private:
        some_operation() { state s = good; /* ... */ }
        // ...
};

void f(X& x)
{
        while (x.readstate() == X::good) // ...
}
```

Linkage

The major difference here is that C allows

```
extern void f();
/* no declaration of g */

main()
{
        f(3,4);         /* legal C, illegal C++ */
        g(5,6);         /* legal C, illegal C++ */
}
```

and C++ does not.

In C++, a function prototype with no arguments means that the function has no arguments, and it is an error to call it with arguments. The ANSI C standard lists this (mis)use of function declarations as obsolescent (§3.9.4). We think C++ is an excellent place to institute this disappearance.

To declare a function `f()` with no arguments in a way that unambiguously means the same thing in both C and C++, say something like this:

```
int getcount(void);
```

Furthermore, in C++, a prototype is required for *any* call; an undeclared function cannot be called. This is absolutely fundamental to the type safety of C++; C requires a prototype only for functions, such as `printf()`, that accept variable numbers of arguments.

Linkage Consistency

C++ requires the types of all objects and functions with external linkage to be consistent across separate compilations – and enforces this requirement. This implies that all prototypes for a function must agree (exactly) and that any structure tag used in the type of any object or function with external linkage must refer to the same structure (with the same name) in all files.

We are not convinced that this requirement is actually different from C but we are convinced that actual C practice is such that enforcing the requirement would be unacceptable because it would break too much code.

C++ relies on name equivalence; that is, two types are considered the same if and only if they have the same name – and there must be exactly one definition of a given type in given scope. ANSI C allows certain examples of structural equivalence; that is, two types are in a few cases considered the same provided their declarations are sufficiently similar. For example:

```
// file1:
struct S { int a, int b; };
extern int f(struct S);

// file2:
int f(struct { int a, int b; } arg) { /* ... */ };
```

This example is ANSI C because the declarations of the structures used as the argument type for `f()` are sufficiently similar. In C++, the `f()` in `file2` is not considered a definition of the `f()` declared in `file1` because they have different argument types.

Linkage of `const`

Global variables declared `const` have external linkage by default in C; in C++ such `const`s have internal linkage by default. The reason for this is to avoid having to allocate memory for things that, in our experience, are usually intended as the equivalent of preprocessor macros and to allow systematic use of integer `const`s in constant expressions. For example:

```
const SIZE = 100;
int table[SIZE];          /* legal C++, illegal C */
```

Again this is not as much of a problem as one might expect. It makes no difference, of course, if a constant is only defined and used in a single file or if the `const` is local. If the same constant is defined in several files, the programmer will have to declare it `static` anyway to avoid multiple definition errors from the linker or declare it `extern` in all files but one. All uses of `const` where explicit `static` or `extern` is used are compatible as are all uses of local `const`s.

The only case to look out for is:

```
file1:
        const a = 1;

file2:
        extern const a;
```

which will not link in C++ because no definition will be found for the a referenced in `file2`. The following modification makes the C program acceptable to a C++ compiler:

```
file1:
        extern const a = 1;

file2:
        extern const a;
```

Keywords

C++ has a few extra keywords: `asm`, `catch`, `class`, `delete`, `friend`, `inline`, `new`, `operator`, `private`, `protected`, `public`, `template`, `this`, `try`, and `virtual`. This can't be helped; one cannot add fundamental concepts to a language in a reasonable way without introducing words to refer to those concepts. To avoid chaos, such words must be reserved in languages such as C and C++.

Miscellaneous

The differences mentioned above are the most important because they affect the interface between C and C++ programs and limit – if only insignificantly – what can be expressed in header files shared by the the two languages. The relative insignificance of these limitations can be seen from the fact that all the ANSI C standard library header files are also legal C++ header files.

Other differences are limited to individual source files and are less important since no significant C++ program can pass a C compiler anyway.

Assignment of `void`

C not only allows any object pointer to be assigned to a `void*` but also a `void*` to be assigned to any object pointer. This opens a blatant hole in the type system that was not present in classic C.

We surmise that the reason this is considered acceptable is that C already has a worse hole in its type system in the form of unchecked function arguments and because it provides the C programmer the convenience of not having to cast the results of calling `malloc()`, `calloc()`, etc. Opening this hole is not acceptable in C++ where reliance on the type system is greater. In C++, only the harmless assignment of any object pointer to a `void*` (and not the opposite assignment) is accepted. Furthermore, since C++ programmers use operator `new` in preference to using `malloc()`, etc., directly, the hole in the type system would provide no extra convenience in C++.

In a similar vein, C++ does not allow a pointer to a `const` object to be assigned to `void*`: the program must use a `const void*` instead. This is to catch things like:

```
extern "C" {
        int read(int, void, int);
        int write(int, const void, int);
}

const char filename[] = "/etc/passwd";

void f()
{
        read(0, filename, sizeof(filename)); // read into a const?
}
```

If an arbitrary `const` pointer could be freely assigned to `void*`, there would be no way for the compiler to detect that this program fragment tries to read into a constant array.

Of course a C++ program can use a cast to convert a `void*` to or from any other kind of pointer.

Type of `'a'`

The type of character constants in C++ is `char` instead of `int`. However, since the rules for determining the integer value of a character constant are identical in C and C++ the only way to detect this in a C program is with an expression like `sizeof('a')`. In C++, however, it is essential for the overloaded function resolution mechanism to resolve `'a'` as a `char` so that

```
cout << 'a';
```

can print `a` instead of `97`.

For the same reason, the type of an enumerator is the type of its enumeration. This *may* lead to an incompatibility since, given

```
enum e { A, B };
```

`sizeof(A)==sizeof(enum e)` and `sizeof(enum e)` are not guaranteed to be equal to `sizeof(int)` in either C or C++ .

Repeated Definition

In C++, a "plain" global object declaration (without `extern` or an initializer) is a definition. Two of those in a file give a double definition error. For example:

```
int i;
int i;
```

In C, this is accepted. The reason for the difference is again the uniform treatment of built-in and user-defined types. Suppose `Int` is a class for which a constructor taking no arguments has been declared:

```
Int i;
Int i;
```

Each declaration requires a call of the constructor and each places that call in the sequence of such calls to be executed for the file. Deciding that only one of the declarations is "real" and ignoring the other not only adds complexity to C++ compilers and/or linkers but can also introduce dependency errors into the dynamic initialization.

Character Array Initialization

For some reason C has come to allow the previously illegal initialization

```
char v[3] = "asd";
```

Allowing this violates the rule that strings are terminated by `'\0'` so C++ still rejects it. The way to initialize a bounded character array that is not intended to be used as a string is to initialize the individual elements:

```
char v[3] = { 'a', 's', 'd' };
```

`goto` Skipping Initialization

The following is legal C, but not C++:

```
void f()
{
        /* ... */
        goto l1;
        {
                int a = 7;
                String b = "asdf";
        l1:
                /* ... */
        }
        /* ... */
}
```

In C, this is merely dangerous and bad style. In C++, it would with great regularity cause core dumps; that innocuous looking `String` might be a class for which a destructor will be called on exit from `f()`.

`enum` Assignment

In C, an `int` may be assigned to a variable of an enumeration type. For example:

```
enum e { A, B };

enum e obj1 = 7;

enum e obj2 = 257;          /* what if an e is represented by a char? */
```

C leaves the meaning of many such assignments implementation dependent and the ANSI C manual recommends a warning against all such assignments. C++ prohibits them. As usual, casting can defeat type checking:

```
enum e obj3 = (enum e) 7;          /* caveat emptor */
```

Comments

It was believed that the introduction of // comments in C++ did not lead to any incompatibilities. Here is a counter example:

```
main()
{
        int a = 4;
        int b = 8//* divide by a*/a;
        +a;
}
```

Note that the use of a prefix operator starting the line is essential, as is the absence of whitespace. We do not consider this incompatibility serious enough to abandon either style of comments.

We note in passing that it is important to cater to // comments in the preprocessor too, lest the following evoke surprising preprocessor complaints:

```
#include <stdio.h>

int flag;          // remember if we have called getc()
```

Conclusion

We have tried to summarize the differences between ANSI C and C++. In the design of C++, we have been trying to keep the differences as minor as possible. We believe that we have succeeded in this beyond reasonable expectations and that differences that remain are unimportant to C programmers, essential to C++ programmers, and stem from the somewhat different purposes behind C and C++ .

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