User's Guide to the GNU C++ Library

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for version 2.0

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Note: The GNU C++ library is still in test release. You will be performing a valuable service if you report any bugs you encounter.

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Version 2, June 1991

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Contributors to GNU C++ library

Aside from Michael Tiemann, who worked out the front end for GNU C++, and Richard Stallman, who worked out the back end, the following people (not including those who have made their contributions to GNU CC) should not go unmentioned.

- Doug Lea contributed most otherwise unattributed classes.
- Per Bothner contributed the iostream I/O classes.
- Dirk Grunwald contributed the Random number generation classes, and PairingHeaps.
- Kurt Baudendistel contributed Fixed precision reals.
- Doug Schmidt contributed ordered hash tables, a perfect hash function generator, and several other utilities.
- Marc Shapiro contributed the ideas and preliminary code for Plexes.
- Eric Newton contributed the curses window classes.
- Some of the I/O code is derived from BSD 4.4, and was developed by the University of California, Berkeley.
- The code for converting accurately between floating point numbers and their string representations was written by David M. Gay of AT&T.

1 Installing GNU C++ library

1. Read through the README file and the Makefile. Make sure that all paths, system-dependent compile switches, and program names are correct.
2. Check that files ‘`values.h`’, ‘`stdio.h`’, and ‘`math.h`’ declare and define values appropriate for your system.
3. Type ‘`make all`’ to compile the library, test, and install. Current details about contents of the tests and utilities are in the ‘`README`’ file.

2 Trouble in Installation

Here are some of the things that have caused trouble for people installing GNU C++ library.

1. Make sure that your GNU C++ version number is at least as high as your libg++ version number. For example, libg++ 1.22.0 requires g++ 1.22.0 or later releases.
2. Double-check system constants in the header files mentioned above.

3 GNU C++ library aims, objectives, and limitations

The GNU C++ library, libg++ is an attempt to provide a variety of C++ programming tools and other support to GNU C++ programmers.

Differences in distribution policy are only part of the difference between libg++.a and AT&T libC.a. libg++ is not intended to be an exact clone of libC. For one, libg++ contains bits of code that depend on special features of GNU g++ that are either different or lacking in the AT&T version, including slightly different inlining and overloading strategies, dynamic local arrays, etc. All of these differences are minor. For example, while the AT&T and GNU stream classes are implemented in very different ways, the vast majority of C++ programs compile and run under either version with no visible difference. Additionally, all g++-specific constructs are conditionally compiled; The library is designed to be compatible with any 2.0 C++ compiler.

libg++ has also contained workarounds for some limitations in g++: both g++ and libg++ are still undergoing rapid development and testing—a task that is helped tremendously by the feedback of active users. This manual is also still under development; it has some catching up to do to include all the facilities now in the library.

libg++ is not the only freely available source of C++ class libraries. Some notable alternative sources are Interviews and NIHCL. (InterViews has been available on the X-windows X11 tapes and also from interviews.stanford.edu. NIHCL is available by anonymous ftp from GNU archives (such as the pub directory of prep.ai.mit.edu), although it is not supported by the FSF - and needs some work before it will work with g++.)

As every C++ programmer knows, the design (moreso than the implementation) of a C++ class library is something of a challenge. Part of the reason is that C++ supports two, partially incompatible, styles of object-oriented programming – The "forest" approach, involving a collection of free-standing classes that can be mixed and matched, versus the completely hierarchical (smalltalk style) approach, in which all classes are derived from a common ancestor. Of course, both styles have advantages and disadvantages. So far, libg++ has adopted the "forest" approach. Keith Gorlen's OOPS library adopts the hierarchical approach, and may be an attractive alternative for C++ programmers who prefer this style.

Currently (and/or in the near future) libg++ provides support for a few basic kinds of classes:

The first kind of support provides an interface between C++ programs and C libraries. This includes basic header files (like '`stdio.h`') as well as things like the File and stream classes. Other classes that interface to other aspects of C libraries (like those that maintain environmental information) are in various stages of development; all will undergo implementation modifications when the forthcoming GNU libc library is released.

The second kind of support contains general-purpose basic classes that transparently manage variable-sized objects on the freestore. This includes Obstacks, multiple-precision Integers and Rationals, arbitrary length Strings, BitSets, and BitStrings.

Third, several classes and utilities of common interest (e.g., Complex numbers) are provided.

Fourth, a set of pseudo-generic prototype files are available as a mechanism for generating common container classes. These are described in more detail in the introduction

to container prototypes. Currently, only a textual substitution mechanism is available for generic class creation.

4 GNU C++ library stylistic conventions

- C++ source files have file extension '`.cc`'. Both C-compatibility header files and class declaration files have extension '`.h`'.
- C++ class names begin with capital letters, except for `istream` and `ostream`, for AT&T C++ compatibility. Multi-word class names capitalize each word, with no underscore separation.
- Include files that define C++ classes begin with capital letters (as do the names of the classes themselves). '`stream.h`' is uncapitalized for AT&T C++ compatibility.
- Include files that supply function prototypes for other C functions (system calls and libraries) are all lower case.
- All include files define a preprocessor variable _X_h, where X is the name of the file, and conditionally compile only if this has not been already defined. The `#pragma once` facility is also used to avoid re-inclusion.
- Structures and objects that must be publicly defined, but are not intended for public use have names beginning with an underscore. (for example, the `_Srep` struct, which is used only by the String and SubString classes.)
- The underscore is used to separate components of long function names, e.g., `set_File_exception_handler()`.
- When a function could be usefully defined either as a member or a friend, it is generally a member if it modifies and/or returns itself, else it is a friend. There are cases where naturalness of expression wins out over this rule.
- Class declaration files are formatted so that it is easy to quickly check them to determine function names, parameters, and so on. Because of the different kinds of things that may appear in class declarations, there is no perfect way to do this. Any suggestions on developing a common class declaration formatting style are welcome.
- All classes use the same simple error (exception) handling strategy. Almost every class has a member function named `error(char* msg)` that invokes an associated error handler function via a pointer to that function, so that the error handling function may be reset by programmers. By default nearly all call `*lib_error_handler`, which prints the message and then aborts execution. This system is subject to change. In general, errors are assumed to be non-recoverable: Library classes do not include code that allows graceful continuation after exceptions.

5 Support for representation invariants

Most GNU C++ library classes possess a method named `OK()`, that is useful in helping to verify correct performance of class operations.

The `OK()` operations checks the "representation invariant" of a class object. This is a test to check whether the object is in a valid state. In effect, it is a (sometimes partial) verification of the library's promise that (1) class operations always leave objects in valid states, and (2) the class protects itself so that client functions cannot corrupt this state.

While no simple validation technique can assure that all operations perform correctly, calls to `OK()` can at least verify that operations do not corrupt representations. For example for `String a, b, c; ... a = b + c;`, a call to `a.OK();` will guarantee that `a` is a valid `String`, but does not guarantee that it contains the concatenation of `b + c`. However, given that `a` is known to be valid, it is possible to further verify its properties, for example via `a.after(b) == c && a.before(c) == b`. In other words, `OK()` generally checks only those internal representation properties that are otherwise inaccessible to users of the class. Other class operations are often useful for further validation.

Failed calls to `OK()` call a class's `error` method if one exists, else directly call `abort`. Failure indicates an implementation error that should be reported.

With only rare exceptions, the internal support functions for a class never themselves call `OK()` (although many of the test files in the distribution call `OK()` extensively).

Verification of representational invariants can sometimes be very time consuming for complicated data structures.

6 Introduction to container class prototypes

As a temporary mechanism enabling the support of generic classes, the GNU C++ Library distribution contains a directory ('`g++-include`') of files designed to serve as the basis for generating container classes of specified elements. These files can be used to generate '`.h`' and '`.cc`' files in the current directory via a supplied shell script program that performs simple textual substitution to create specific classes.

While these classes are generated independently, and thus share no code, it is possible to create versions that do share code among subclasses. For example, using `typedef void* ent`, and then generating a `entList` class, other derived classes could be created using the `void*` coercion method described in Stroustrup, pp204-210.

This very simple class-generation facility is useful enough to serve current purposes, but will be replaced with a more coherent mechanism for handling C++ generics in a way that minimally disrupts current usage. Without knowing exactly when or how parametric classes might be added to the C++ language, provision of this simplest possible mechanism, textual substitution, appears to be the safest strategy, although it does require certain redundancies and awkward constructions.

Specific classes may be generated via the '`genclass`' shell script program. This program has arguments specifying the kinds of base types(s) to be used. Specifying base types requires two arguments. The first is the name of the base type, which may be any named type, like `int` or `String`. Only named types are supported; things like `int*` are not accepted. However, pointers like this may be used by supplying the appropriate typedefs (e.g., editing the resulting files to include `typedef int* intp;`). The type name must be followed by one of the words `val` or `ref`, to indicate whether the base elements should be passed to functions by-value or by-reference.

You can specify basic container classes using `genclass base [val,ref] proto`, where `proto` is the name of the class being generated. Container classes like dictionaries and maps that require two types may be specified via `genclass -2 keytype [val, ref], basetype [val, ref] proto`, where the key type is specified first and the contents type second. The resulting classnames and filenames are generated by prepending the specified type names to the prototype names, and separating the filename parts with dots. For example, `genclass int val List` generates class `intList` residing in files '`int.List.h`' and '`int.List.cc`'. `genclass -2 String ref int val VHMap` generates (the awkward, but unavoidable) class name `StringintVHMap`. Of course, programmers may use `typedef` or simple editing to create more appropriate names. The existence of dot seperators in file names allows the use of GNU make to help automate configuration and recompilation. An example Makefile exploiting such capabilities may be found in the '`libg++/proto-kit`' directory.

The `genclass` utility operates via simple text substitution using `sed`. All occurrences of the pseudo-types `<T>` and `<C>` (if there are two types) are replaced with the indicated type, and occurrences of `<T&>` and `<C&>` are replaced by just the types, if `val` is specified, or types followed by "&" if `ref` is specified.

Programmers will frequently need to edit the '`.h`' file in order to insert additional `#include` directives or other modifications. A simple utility, '`prepend-header`' to prepend other '`.h`' files to generated files is provided in the distribution.

One dubious virtue of the prototyping mechanism is that, because sources files, not archived library classes, are generated, it is relatively simple for programmers to modify container classes in the common case where slight variations of standard container classes are required.

It is often a good idea for programmers to archive (via `ar`) generated classes into '`.a`' files so that only those class functions actually used in a given application will be loaded. The test subdirectory of the distribution shows an example of this.

Because of `#pragma interface` directives, the '`.cc`' files should be compiled with `-O` or `-DUSE_LIBGXX_INLINES` enabled.

Many container classes require specifications over and above the base class type. For example, classes that maintain some kind of ordering of elements require specification of a comparison function upon which to base the ordering. This is accomplished via a prototype file '`defs.hP`' that contains macros for these functions. While these macros default to perform reasonable actions, they can and should be changed in particular cases. Most prototypes require only one or a few of these. No harm is done if unused macros are defined to perform nonsensical actions. The macros are:

`DEFAULT_INITIAL_CAPACITY`
: The initial capacity for containers (e.g., hash tables) that require an initial capacity argument for constructors. Default: 100

`<T>EQ(a, b)`
: return true if a is considered equal to b for the purposes of locating, etc., an element in a container. Default: (a == b)

`<T>LE(a, b)`
: return true if a is less than or equal to b Default: (a <= b)

`<T>CMP(a, b)`
: return an integer < 0 if a<b, 0 if a==b, or > 0 if a>b. Default: (a <= b)? (a==b)? 0 : -1 : 1

`<T>HASH(a)`
: return an unsigned integer representing the hash of a. Default: hash(a) ; where extern unsigned int hash(<T&>). (note: several useful hash functions are declared in builtin.h and defined in hash.cc)

Nearly all prototypes container classes support container traversal via `Pix` pseudo indices, as described elsewhere.

All object containers must perform either a `X::X(X&)` (or `X::X()` followed by `X::operator =(X&)`) to copy objects into containers. (The latter form is used for containers built from C++ arrays, like `VHSets`). When containers are destroyed, they invoke `X::~X()`. Any objects used in containers must have well behaved constructors and destructors. If you want to create containers that merely reference (point to) objects that reside elsewhere, and are not copied or destroyed inside the container, you must use containers of pointers, not containers of objects.

All prototypes are designed to generate *HOMOGENOUS* container classes. There is no universally applicable method in C++ to support heterogenous object collections with

elements of various subclasses of some specified base class. The only way to get heterogenous structures is to use collections of pointers-to-objects, not collections of objects (which also requires you to take responsibility for managing storage for the objects pointed to yourself).

For example, the following usage illustrates a commonly encountered danger in trying to use container classes for heterogenous structures:

```
class Base { int x; ...}
class Derived : public Base { int y; ... }

BaseVHSet s; // class BaseVHSet generated via something like
             // 'genclass Base ref VHSet'

void f()
{
  Base b;
  s.add(b); // OK

  Derived d;
  s.add(d);  // (CHOP!)
}
```

At the line flagged with '`(CHOP!)`', a `Base::Base(Base&)` is called inside `Set::add(Base&)`—*not* `Derived::Derived(Derived&)`. Actually, in `VHSet`, a `Base::operator=(Base&)`, is used instead to place the element in an array slot, but with the same effect. So only the Base part is copied as a `VHSet` element (a so-called chopped-copy). In this case, it has an `x` part, but no `y` part; and a Base, not Derived, vtable. Objects formed via chopped copies are rarely sensible.

To avoid this, you must resort to pointers:

```
typedef Base* BasePtr;

BasePtrVHSet s; // class BaseVHSet generated via something like
                // 'genclass BasePtr val VHSet'

void f()
{
  Base* bp = new Base;
  s.add(b);

  Base* dp = new Derived;
  s.add(d);  // works fine.

  // Don't forget to delete bp and dp sometime.
  // The VHSet won't do this for you.
}
```

6.1 Example

The prototypes can be difficult to use on first attempt. Here is an example that may be helpful. The utilities in the '`proto-kit`' simplify much of the actions described, but are not used here.

Suppose you create a class `Person`, and want to make an Map that links the social security numbers associated with each person. You start off with a file '`Person.h`'

```
#include <String.h>

class Person
{
  String nm;
  String addr;
  //...
public:
  const String& name() { return nm; }
  const String& address() { return addr; }
  void          print() { ... }
  //...
}
```

And in file '`SSN.h`',

```
typedef unsigned int SSN;
```

Your first decision is what storage/usage strategy to use. There are several reasonable alternatives here: You might create an "object collection" of Persons, a "pointer collection" of pointers-to-Persons, or even a simple String map, housing either copies of pointers to the names of Persons, since other fields are unused for purposes of the Map. In an object collection, instances of class Person "live" inside the Map, while in a pointer collection, the instances live elsewhere. Also, as above, if instances of subclasses of Person are to be used inside the Map, you must use pointers. In a String Map, the same difference holds, but now only for the name fields. Any of these choices might make sense in particular applications.

The second choice is the Map implementation strategy. Either a tree or a hash table might make sense. Suppose you want an AVL tree Map. There are two things to now check. First, as an object collection, the AVLMap requires that the elsement class contain an `X(X&)` constructor. In C++, if you don't specify such a constructor, one is constructed for you, but it is a very good idea to always do this yourself, to avoid surprises. In this example, you'd use something like

```
class Person
{ ...;
    Person(const Person& p) :nm(p.nm), addr(p.addr) {}
};
```

Also, an AVLMap requires a comparison function for elements in order to maintain order. Rather than requiring you to write a particular comparison function, a '`defs`' file is consulted to determine how to compare items. You must create and edit such a file.

Before creating '`Person.defs.h`', you must first make one additional decision. Should the Map member functions like `m.contains(p)` take arguments (`p`) by reference (i.e., typed as `int Map::contains(const Person& p)` or by value (i.e., typed as `int Map::contains(const Person p)`. Generally, for user-defined classes, you want to pass by reference, and for builtins and pointers, to pass by value. SO you should pick by-reference.

You can now create '`Person.defs.h`' via `genclass Person ref defs`. This creates a simple skeleton that you must edit. First, add `#include "Person.h"` to the top. Second, edit the `<T>CMP(a,b)` macro to compare on name, via

```
#define <T>CMP(a, b) ( compare(a.name(), b.name()) )
```

which invokes the `int compare(const String&, const String&)` function from '`String.h`'. Of course, you could define this in any other way as well. In fact, the default versions in the skeleton turn out to be OK (albeit inefficient) in this particular example.

You may also want to create file '`SSN.defs.h`'. Here, choosing call-by-value makes sense, and since no other capabilities (like comparison functions) of the SSNs are used (and the defaults are OK anyway), you'd type

```
genclass SSN val defs
```

and then edit to place `#include "SSN.h"` at the top.

Finally, you can generate the classes. First, generate the base class for Maps via

```
genclass -2 Person ref SSN val Map
```

This generates only the abstract class, not the implementation, in file '`Person.SSN.Map.h`' and '`Person.SSN.Map.cc`'. To create the AVL implementation, type

```
genclass -2 Person ref SSN val AVLMap
```

This creates the class `PersonSSNAVLMap`, in '`Person.SSN.AVLMap.h`' and '`Person.SSN.AVLMap.cc`'.

To use the AVL implementation, compile the two generated '`.cc`' files, and specify '`#include "Person.SSN.AVLMap.h"`' in the application program. All other files are included in the right ways automatically.

One last consideration, peculiar to Maps, is to pick a reasonable default contents when declaring an AVLMap. Zero might be appropriate here, so you might declare a Map,

```
PersonSSNAVLMap m((SSN)0);
```

Suppose you wanted a `VHMap` instead of an `AVLMap` Besides generating different implementations, there are two differences in how you should prepare the '`defs`' file. First, because a VHMap uses a C++ array internally, and because C++ array slots are initialized differently than single elements, you must ensure that class Person contains (1) a no-argument constructor, and (2) an assignment operator. You could arrange this via

```
class Person
{ ...;
    Person() {}
  void operator = (const Person& p) { nm = p.nm; addr = p.addr; }
};
```

(The lack of action in the constructor is OK here because `Strings` possess usable no-argument constructors.)

You also need to edit '`Person.defs.h`' to indicate a usable hash function and default capacity, via something like

```
#include <builtin.h>
#define <T>HASH(x)  (hashpjw(x.name().chars()))
#define DEFAULT_INITIAL_CAPACITY 1000
```

Since the `hashpjw` function from '`builtin.h`' is appropriate here. Changing the default capacity to a value expected to exceed the actual capacity helps to avoid "hidden" inefficiencies when a new VHMap is created without overriding the default, which is all too easy to do.

Otherwise, everything is the same as above, substituting `VHMap` for `AVLMap`.

7 Variable-Sized Object Representation

One of the first goals of the GNU C++ library is to enrich the kinds of basic classes that may be considered as (nearly) "built into" C++. A good deal of the inspiration for these efforts is derived from considering features of other type-rich languages, particularly Common Lisp and Scheme. The general characteristics of most class and friend operators and functions supported by these classes has been heavily influenced by such languages.

Four of these types, Strings, Integers, BitSets, and BitStrings (as well as associated and/or derived classes) require representations suitable for managing variable-sized objects on the free-store. The basic technique used for all of these is the same, although various details necessarily differ from class to class.

The general strategy for representing such objects is to create chunks of memory that include both header information (e.g., the size of the object), as well as the variable-size data (an array of some sort) at the end of the chunk. Generally the maximum size of an object is limited to something less than all of addressable memory, as a safeguard. The minimum size is also limited so as not to waste allocations expanding very small chunks. Internally, chunks are allocated in blocks well-tuned to the performance of the `new` operator.

Class elements themselves are merely pointers to these chunks. Most class operations are performed via inline "translation" functions that perform the required operation on the corresponding representation. However, constructors and assignments operate by copying entire representations, not just pointers.

No attempt is made to control temporary creation in expressions and functions involving these classes. Users of previous versions of the classes will note the disappearance of both "Tmp" classes and reference counting. These were dropped because, while they did improve performance in some cases, they obscure class mechanics, lead programmers into the false belief that they need not worry about such things, and occasionally have paradoxical behavior.

These variable-sized object classes are integrated as well as possible into C++. Most such classes possess converters that allow automatic coercion both from and to builtin basic types. (e.g., char* to and from String, long int to and from Integer, etc.). There are pro's and con's to circular converters, since they can sometimes lead to the conversion from a builtin type through to a class function and back to a builtin type without any special attention on the part of the programmer, both for better and worse.

Most of these classes also provide special-case operators and functions mixing basic with class types, as a way to avoid constructors in cases where the operations do not rely on anything special about the representations. For example, there is a special case concatenation operator for a String concatenated with a char, since building the result does not rely on anything about the String header. Again, there are arguments both for and against this approach. Supporting these cases adds a non-trivial degree of (mainly inline) function proliferation, but results in more efficient operations. Efficiency wins out over parsimony here, as part of the goal to produce classes that provide sufficient functionality and efficiency so that programmers are not tempted to try to manipulate or bypass the underlying representations.

8 Some guidelines for using expression-oriented classes

The fact that C++ allows operators to be overloaded for user-defined classes can make programming with library classes like `Integer`, `String`, and so on very convenient. However, it is worth becoming familiar with some of the inherent limitations and problems associated with such operators.

Many operators are *constructive*, i.e., create a new object based on some function of some arguments. Sometimes the creation of such objects is wasteful. Most library classes supporting expressions contain facilities that help you avoid such waste.

For example, for `Integer a, b, c; ...; c = a + b + a;`, the plus operator is called to sum a and b, creating a new temporary object as its result. This temporary is then added with a, creating another temporary, which is finally copied into c, and the temporaries are then deleted. In other words, this code might have an effect similar to `Integer a, b, c; ...; Integer t1(a); t1 += b; Integer t2(t1); t2 += a; c = t2;`.

For small objects, simple operators, and/or non-time/space critical programs, creation of temporaries is not a big problem. However, often, when fine-tuning a program, it may be a good idea to rewrite such code in a less pleasant, but more efficient manner.

For builtin types like ints, and floats, C and C++ compilers already know how to optimize such expressions to reduce the need for temporaries. Unfortunately, this is not true for C++ user defined types, for the simple (but very annoying, in this context) reason that nothing at all is guaranteed about the semantics of overloaded operators and their interrelations. For example, if the above expression just involved ints, not Integers, a compiler might internally convert the statement into something like `c = a; c += b; c+= a;` , or perhaps something even more clever. But since C++ does not know that Integer operator += has any relation to Integer operator +, A C++ compiler cannot do this kind of expression optimization itself.

In many cases, you can avoid construction of temporaries simply by using the assignment versions of operators whenever possible, since these versions create no temporaries. However, for maximum flexibility, most classes provide a set of "embedded assembly code" procedures that you can use to fully control time, space, and evaluation strategies. Most of these procedures are "three-address" procedures that take two `const` source arguments, and a destination argument. The procedures perform the appropriate actions, placing the results in the destination (which is may involve overwriting old contents). These procedures are designed to be fast and robust. In particular, aliasing is always handled correctly, so that, for example `add(x, x, x);` is perfectly OK. (The names of these procedures are listed along with the classes.)

For example, suppose you had an Integer expression `a = (b - a) * -(d / c);`

This would be compiled as if it were `Integer t1=b-a; Integer t2=d/c; Integer t3=-t2; Integer t4=t1*t3; a=t4;`

But, with some manual cleverness, you might yourself some up with `sub(a, b, a); mul(a, d, a); div(a, c, a);`

A related phenomenon occurs when creating your own constructive functions returning instances of such types. Suppose you wanted to write function `Integer f(const Integer& a) { Integer r = a; r += a; return r; }`

This function, when called (as in `a = f(a);`) demonstrates a similar kind of wasted copy. The returned value r must be copied out of the function before it can be used by the caller. In GNU C++, there is an alternative via the use of named return values. Named return values allow you to manipulate the returned object directly, rather than requiring you to create a local inside a function and then copy it out as the returned value. In this example, this can be done via `Integer f(const Integer& a) return r(a) { r += a; return; }`

A final guideline: The overloaded operators are very convenient, and much clearer to use than procedural code. It is almost always a good idea to make it right, *then* make it fast, by translating expression code into procedural code after it is known to be correct.

9 Pseudo-indexes

Many useful classes operate as containers of elements. Techniques for accessing these elements from a container differ from class to class. In the GNU C++ library, access methods have been partially standardized across different classes via the use of pseudo-indexes called `Pixes`. A `Pix` acts in some ways like an index, and in some ways like a pointer. (Their underlying representations are just `void*` pointers). A `Pix` is a kind of "key" that is translated into an element access by the class. In virtually all cases, `Pixes` are pointers to some kind internal storage cells. The containers use these pointers to extract items.

`Pixes` support traversal and inspection of elements in a collection using analogs of array indexing. However, they are pointer-like in that `0` is treated as an invalid `Pix`, and unsafe insofar as programmers can attempt to access nonexistent elements via dangling or otherwise invalid `Pixes` without first checking for their validity.

In general it is a very bad idea to perform traversals in the the midst of destructive modifications to containers.

Typical applications might include code using the idiom

```
for (Pix i = a.first(); i != 0; a.next(i)) use(a(i));
```

for some container `a` and function `use`.

Classes supporting the use of `Pixes` always contain the following methods, assuming a container `a` of element types of `Base`.

`Pix i = a.first()`
: Set i to index the first element of a or 0 if a is empty.

`a.next(i)`
: advance i to the next element of a or 0 if there is no next element;

`Base x = a(i); a(i) = x;`
: a(i) returns a reference to the element indexed by i.

`int present = a.owns(i)`
: returns true if Pix i is a valid Pix in a. This is often a relatively slow operation, since the collection must usually traverse through elements to see if any correspond to the Pix.

Some container classes also support backwards traversal via

`Pix i = a.last()`
: Set i to the last element of a or 0 if a is empty.

`a.prev(i)`
: sets i to the previous element in a, or 0 if there is none.

Collections supporting elements with an equality operation possess

`Pix j = a.seek(x)`
: sets j to the index of the first occurrence of x, or 0 if x is not contained in a.

Bag classes possess

`Pix j = a.seek(x, Pix from = 0)`
: sets j to the index of the next occurrence of x following i, or 0 if x is not contained in a. If i == 0, the first occurrence is returned.

Set, Bag, and PQ classes possess

`Pix j = a.add(x) (or a.enq(x) for priority queues)`
: add x to the collection, returning its Pix. The Pix of an item can change in collections where further additions and deletions involve the actual movement of elements (currently in OXPSet, OXPBag, XPPQ, VOHSet), but in all other cases, an item's Pix may be considered a permanent key to its location.

10 Header files for interfacing C++ to C

The following files are provided so that C++ programmers may invoke common C library and system calls. The names and contents of these files are subject to change in order to be compatible with the forthcoming GNU C library. Other files, not listed here, are simply C++-compatible interfaces to corresponding C library files.

‘`values.h`’
: A collection of constants defining the numbers of bits in builtin types, minimum and maximum values, and the like. Most names are the same as those found in ‘`values.h`’ found on Sun systems.

‘`std.h`’
: A collection of common system calls and ‘`libc.a`’ functions. Only those functions that can be declared without introducing new type definitions (socket structures, for example) are provided. Common `char*` functions (like `strcmp`) are among the declarations. All functions are declared along with their library names, so that they may be safely overloaded.

‘`string.h`’
: This file merely includes ‘`<std.h>`’, where string function prototypes are declared. This is a workaround for the fact that system ‘`string.h`’ and ‘`strings.h`’ files often differ in contents.

‘`osfcn.h`’
: This file merely includes ‘`<std.h>`’, where system function prototypes are declared.

‘`libc.h`’
: This file merely includes ‘`<std.h>`’, where C library function prototypes are declared.

‘`math.h`’
: A collection of prototypes for functions usually found in libm.a, plus some `#defined` constants that appear to be consistent with those provided in the AT&T version. The value of `HUGE` should be checked before using. Declarations of all common math functions are preceded with `overload` declarations, since these are commonly overloaded.

‘`stdio.h`’
: Declaration of `FILE` (`_iobuf`), common macros (like `getc`), and function prototypes for ‘`libc.a`’ functions that operate on `FILE*`’s. The value `BUFSIZ` and the declaration of `_iobuf` should be checked before using.

‘`assert.h`’
: C++ versions of assert macros.

‘`generic.h`’
: String concatenation macros useful in creating generic classes. They are similar in function to the AT&T CC versions.

‘`new.h`’
: Declarations of the default global operator new, the two-argument placement version, and associated error handlers.

11 Utility functions for built in types

Files '`builtin.h`' and corresponding '`.cc`' implementation files contain various convenient inline and non-inline utility functions. These include useful enumeration types, such as `TRUE`, `FALSE` ,the type definition for pointers to libg++ error handling functions, and the following functions.

`long abs(long x); double abs(double x);`
: inline versions of abs. Note that the standard libc.a version, `int abs(int)` is *not* declared as inline.

`void clearbit(long& x, long b);`
: clears the b'th bit of x (inline).

`void setbit(long& x, long b);`
: sets the b'th bit of x (inline)

`int testbit(long x, long b);`
: returns the b'th bit of x (inline).

`int even(long y);`
: returns true if x is even (inline).

`int odd(long y);`
: returns true is x is odd (inline).

`int sign(long x); int sign(double x);`
: returns -1, 0, or 1, indicating whether x is less than, equal to, or greater than zero (inline).

`long gcd(long x, long y);`
: returns the greatest common divisor of x and y.

`long lcm(long x, long y);`
: returns the least common multiple of x and y.

`long lg(long x);`
: returns the floor of the base 2 log of x.

`long pow(long x, long y); double pow(double x, long y);`
: returns x to the integer power y using via the iterative O(log y) "Russian peasant" method.

`long sqr(long x); double sqr(double x);`
: returns x squared (inline).

`long sqrt(long y);`
: returns the floor of the square root of x.

`unsigned int hashpjw(const char* s);`
: a hash function for null-terminated char* strings using the method described in Aho, Sethi, & Ullman, p 436.

`unsigned int multiplicativehash(int x);`
: a hash function for integers that returns the lower bits of multiplying x by the golden ratio times pow(2, 32). See Knuth, Vol 3, p 508.

`unsigned int foldhash(double x);`
: a hash function for doubles that exclusive-or's the first and second words of x, returning the result as an integer.

`double start_timer()`
: Starts a process timer.

`double return_elapsed_time(double last_time)`
: Returns the process time since last_time. If last_time == 0 returns the time since the last start_timer. Returns -1 if start_timer was not first called.

File '`Maxima.h`' includes versions of `MAX, MIN` for builtin types.

File '`compare.h`' includes versions of `compare(x, y)` for builtin types. These return negative if the first argument is less than the second, zero for equal, and positive for greater.

12 Library dynamic allocation primitives

Libg++ contains versions of `malloc, free, realloc` that were designed to be well-tuned to C++ applications. The source file '`malloc.c`' contains some design and implementation details. Here are the major user-visible differences from most system malloc routines:

1. These routines *overwrite* storage of freed space. This means that it is never permissible to use a `delete`'d object in any way. Doing so will either result in trapped fatal errors or random aborts within malloc, free, or realloc.
2. The routines tend to perform well when a large number of objects of the same size are allocated and freed. You may find that it is not worth it to create your own special allocation schemes in such cases.
3. The library sets top-level `operator new()` to call malloc and `operator delete()` to call free. Of course, you may override these definitions in C++ programs by creating your own operators that will take precedence over the library versions. However, if you do so, be sure to define *both* `operator new()` and `operator delete()`.
4. These routines do *not* support the odd convention, maintained by some versions of malloc, that you may call `realloc` with a pointer that has been `free`'d.
5. The routines automatically perform simple checks on `free`'d pointers that can often determine whether users have accidentally written beyond the boundaries of allocated space, resulting in a fatal error.
6. The function `malloc_usable_size(void* p)` returns the number of bytes actually allocated for `p`. For a valid pointer (i.e., one that has been `malloc`'d or `realloc`'d but not yet `free`'d) this will return a number greater than or equal to the requested size, else it will normally return 0. Unfortunately, a non-zero return can not be an absolutely perfect indication of lack of error. If a chunk has been `free`'d but then re-allocated for a different purpose somewhere elsewhere, then `malloc_usable_size` will return non-zero. Despite this, the function can be very valuable for performing run-time consistency checks.
7. `malloc` requires 8 bytes of overhead per allocated chunk, plus a mmaximum alignment adjustment of 8 bytes. The number of bytes of usable space is exactly as requested, rounded to the nearest 8 byte boundary.
8. The routines do *not* contain any synchronization support for multiprocessing. If you perform global allocation on a shared memory multiprocessor, you should disable compilation and use of libg++ malloc in the distribution '`Makefile`' and use your system version of malloc.

13 The new input/output classes

The iostream classes implement most of the features of AT&T version 2.0 iostream library classes, and most of the features of the ANSI X3J16 library draft (which is based on the AT&T design). These classes are available in `libg++` for convenience and for compatibility with older releases; however, since the iostream classes are licensed under less stringent terms than `libg++`, they are now also available in a separate library called `libio`—and documented in a separate manual, corresponding to that library.

See section "Introduction" in *The GNU C++ Iostream Library*.

14 The old I/O library

WARNING: This chapter describes classes that are *obsolete*. These classes are normally not available when libg++ is installed normally. The sources are currently included in the distribution, and you can configure libg++ to use these classes instead of the new iostream classes. This is only a temporary measure; you should convert your code to use iostreams as soon as possible. The iostream classes provide some compatibility support, but it is very incomplete (there is no longer a `File` class).

14.1 File-based classes

The `File` class supports basic IO on Unix files. Operations are based on common C stdio library functions.

`File` serves as the base class for istreams, ostreams, and other derived classes. It contains the interface between the Unix stdio file library and these more structured classes. Most operations are implemented as simple calls to stdio functions. `File` class operations are also fully compatible with raw system file reads and writes (like the system `read` and `lseek` calls) when buffering is disabled (see below). The `FILE*` stdio file pointer is, however maintained as protected. Classes derived from File may only use the IO operations provided by File, which encompass essentially all stdio capabilities.

The class contains four general kinds of functions: methods for binding `File`s to physical Unix files, basic IO methods, file and buffer control methods, and methods for maintaining logical and physical file status.

Binding and related tasks are accomplished via `File` constructors and destructors, and member functions `open, close, remove, filedesc, name, setname`.

If a file name is provided in a constructor or open, it is maintained as class variable `nm` and is accessible via `name`. If no name is provided, then `nm` remains null, except that `Files` bound to the default files stdin, stdout, and stderr are automatically given the names `(stdin), (stdout), (stderr)` respectively. The function `setname` may be used to change the internal name of the `File`. This does not change the name of the physical file bound to the File.

The member function `close` closes a file. The `~File` destructor closes a file if it is open, except that stdin, stdout, and stderr are flushed but left open for the system to close on program exit since some systems may require this, and on others it does not matter. `remove` closes the file, and then deletes it if possible by calling the system function to delete the file with the name provided in the `nm` field.

14.2 Basic IO

- `read` and `write` perform binary IO via stdio `fread` and `fwrite`.
- `get` and `put` for chars invoke stdio `getc` and `putc` macros.
- `put(const char* s)` outputs a null-terminated string via stdio `fputs`.
- `unget` and `putback` are synonyms. Both call stdio `ungetc`.

14.3 File Control

`flush`, `seek`, `tell`, and `tell` call the corresponding stdio functions.

`flush(char)` and `fill()` call stdio `_flsbuf` and `_filbuf` respectively.

`setbuf` is mainly useful to turn off buffering in cases where nonsequential binary IO is being performed. `raw` is a synonym for `setbuf(_IONBF)`. After a `f.raw()`, using the stdio functions instead of the system `read, write`, etc., calls entails very little overhead. Moreover, these become fully compatible with intermixed system calls (e.g., `lseek(f.filedesc(), 0, 0)`). While intermixing `File` and system IO calls is not at all recommended, this technique does allow the `File` class to be used in conjunction with other functions and libraries already set up to operate on file descriptors. `setbuf` should be called at most once after a constructor or open, but before any IO.

14.4 File Status

File status is maintained in several ways.

A `File` may be checked for accessibility via `is_open()`, which returns true if the File is bound to a usable physical file, `readable()`, which returns true if the File can be read from (opened for reading, and not in a _fail state), or `writable()`, which returns true if the File can be written to.

`File` operations return their status via two means: failure and success are represented via the logical state. Also, the return values of invoked stdio and system functions that return useful numeric values (not just failure/success flags) are held in a class variable accessible via `iocount`. (This is useful, for example, in determining the number of items actually read by the `read` function.)

Like the AT&T i/o-stream classes, but unlike the description in the Stroustrup book, p238, `rdstate()` returns the bitwise OR of `_eof`, `_fail` and `_bad`, not necessarily distinct values. The functions `eof()`, `fail()`, `bad()`, and `good()` can be used to test for each of these conditions independently.

`_fail` becomes set for any input operation that could not read in the desired data, and for other failed operations. As with all Unix IO, `_eof` becomes true only when an input operations fails because of an end of file. Therefore, `_eof` is not immediately true after the last successful read of a file, but only after one final read attempt. Thus, for input operations, `_fail` and `_eof` almost always become true at the same time. `bad` is set for unbound files, and may also be set by applications in order to communicate input corruption. Conversely, `_good` is defined as 0 and is returned by `rdstate()` if all is well.

The state may be modified via `clear(flag)`, which, despite its name, sets the corresponding state_value flag. `clear()` with no arguments resets the state to `_good`. `failif(int cond)` sets the state to `_fail` only if `cond` is true.

Errors occuring during constructors and file opens also invoke the function `error`. `error` in turn calls a resetable error handling function pointed to by the non-member global variable `File_error_handler` only if a system error has been generated. Since `error` cannot tell if the current system error is actually responsible for a failure, it may at times print out spurious messages. Three error handlers are provided. The default, `verbose_File_error_handler` calls the system function `perror` to print the corresponding error

message on standard error, and then returns to the caller. `quiet_File_error_handler` does nothing, and simply returns. `fatal_File_error_handler` prints the error and then aborts execution. These three handlers, or any other user-defined error handlers can be selected via the non-member function `set_File_error_handler`.

All read and write operations communicate either logical or physical failure by setting the `_fail` flag. All further operations are blocked if the state is in a `_fail` or`_bad` condition. Programmers must explicitly use `clear()` to reset the state in order to continue IO processing after either a logical or physical failure. C programmers who are unfamiliar with these conventions should note that, unlike the stdio library, `File` functions indicate IO success, status, or failure solely through the state, not via return values of the functions. The `void*` operator or `rdstate()` may be used to test success. In particular, according to c++ conversion rules, the `void*` coercion is automatically applied whenever the `File&` return value of any `File` function is tested in an `if` or `while`. Thus, for example, an easy way to copy all of stdin to stdout until eof (at which point `get` fails) or some error is `char c; while(cin.get(c) && cout.put(c));`.

The current version of istreams and ostreams differs significantly from previous versions in order to obtain compatibility with AT&T 1.2 streams. Most code using previous versions should still work. However, the following features of `File` are not incorporated in streams (they are still present in `File`): `scan(const char* fmt...), remove(), read(), write(), setbuf(), raw()`. Additionally, the feature of previous streams that allowed free intermixing of stream and stdio input and output is no longer guaranteed to always behave as desired.

15 The Obstack class

The `Obstack` class is a simple rewrite of the C obstack macros and functions provided in the GNU CC compiler source distribution.

Obstacks provide a simple method of creating and maintaining a string table, optimized for the very frequent task of building strings character-by-character, and sometimes keeping them, and sometimes not. They seem especially useful in any parsing application. One of the test files demonstrates usage.

A brief summary:

`grow` places something on the obstack without committing to wrap it up as a single entity yet.

`finish` wraps up a constructed object as a single entity, and returns the pointer to its start address.

`copy` places things on the obstack, and *does* wrap them up. `copy` is always equivalent to first grow, then finish.

`free` deletes something, and anything else put on the obstack since its creation.

The other functions are less commonly needed:

`blank` is like grow, except it just grows the space by size units without placing anything into this space

`alloc` is like `blank`, but it wraps up the object and returns its starting address.

`chunk_size, base, next_free, alignment_mask, size, room`
returns the appropriate class variables.

`grow_fast`
places a character on the obstack without checking if there is enough room.

`blank_fast`
like `blank`, but without checking if there is enough room.

`shrink(int n)`
shrink the current chunk by n bytes.

`contains(void* addr)`
returns true if the Obstack holds the address addr.

Here is a lightly edited version of the original C documentation:

These functions operate a stack of objects. Each object starts life small, and may grow to maturity. (Consider building a word syllable by syllable.) An object can move while it is growing. Once it has been "finished" it never changes address again. So the "top of the stack" is typically an immature growing object, while the rest of the stack is of mature, fixed size and fixed address objects.

These routines grab large chunks of memory, using the GNU C++ `new` operator. On occasion, they free chunks, via `delete`.

Each independent stack is represented by a Obstack.

One motivation for this package is the problem of growing char strings in symbol tables. Unless you are a "fascist pig with a read-only mind" [Gosper's immortal quote from HAKMEM item 154, out of context] you would not like to put any arbitrary upper limit on the length of your symbols.

In practice this often means you will build many short symbols and a few long symbols. At the time you are reading a symbol you don't know how long it is. One traditional method is to read a symbol into a buffer, `realloc()`ating the buffer every time you try to read a symbol that is longer than the buffer. This is beaut, but you still will want to copy the symbol from the buffer to a more permanent symbol-table entry say about half the time.

With obstacks, you can work differently. Use one obstack for all symbol names. As you read a symbol, grow the name in the obstack gradually. When the name is complete, finalize it. Then, if the symbol exists already, free the newly read name.

The way we do this is to take a large chunk, allocating memory from low addresses. When you want to build a symbol in the chunk you just add chars above the current "high water mark" in the chunk. When you have finished adding chars, because you got to the end of the symbol, you know how long the chars are, and you can create a new object. Mostly the chars will not burst over the highest address of the chunk, because you would typically expect a chunk to be (say) 100 times as long as an average object.

In case that isn't clear, when we have enough chars to make up the object, *they are already contiguous in the chunk* (guaranteed) so we just point to it where it lies. No moving of chars is needed and this is the second win: potentially long strings need never be explicitly shuffled. Once an object is formed, it does not change its address during its lifetime.

When the chars burst over a chunk boundary, we allocate a larger chunk, and then copy the partly formed object from the end of the old chunk to the beginning of the new larger chunk. We then carry on accreting characters to the end of the object as we normally would.

A special version of grow is provided to add a single char at a time to a growing object.

Summary:

- We allocate large chunks.
- We carve out one object at a time from the current chunk.
- Once carved, an object never moves.
- We are free to append data of any size to the currently growing object.
- Exactly one object is growing in an obstack at any one time.
- You can run one obstack per control block.
- You may have as many control blocks as you dare.
- Because of the way we do it, you can 'unwind' a obstack back to a previous state. (You may remove objects much as you would with a stack.)

The obstack data structure is used in many places in the GNU C++ compiler.

Differences from the the GNU C version

1. The obvious differences stemming from the use of classes and inline functions instead of structs and macros. The C `init` and `begin` macros are replaced by constructors.

2. Overloaded function names are used for grow (and others), rather than the C `grow`, `grow0`, etc.
3. All dynamic allocation uses the the built-in `new` operator. This restricts flexibility by a little, but maintains compatibility with usual C++ conventions.
4. There are now two versions of finish:
    1. finish() behaves like the C version.
    2. finish(char terminator) adds `terminator`, and then calls `finish()`. This enables the normal invocation of `finish(0)` to wrap up a string being grown character-by-character.
5. There are special versions of grow(const char* s) and copy(const char* s) that add the null-terminated string `s` after computing its length.
6. The shrink and contains functions are provided.

16 The AllocRing class

An AllocRing is a bounded ring (circular list), each of whose elements contains a pointer to some space allocated via `new char[some_size]`. The entries are used cyclicly. The size, n, of the ring is fixed at construction. After that, every nth use of the ring will reuse (or reallocate) the same space. AllocRings are needed in order to temporarily hold chunks of space that are needed transiently, but across constructor-destructor scopes. They mainly useful for storing strings containing formatted characters to print across various functions and coercions. These strings are needed across routines, so may not be deleted in any one of them, but should be recovered at some point. In other words, an AllocRing is an extremely simple minded garbage collection mechanism. The GNU C++ library used to use one AllocRing for such formatting purposes, but it is being phased out, and is now only used by obsolete functions. These days, AllocRings are probably not very useful.

Support includes:

`AllocRing a(int n)`
: constructs an Alloc ring with n entries, all null.

`void* mem = a.alloc(sz)`
: moves the ring pointer to the next entry, and reuses the space if their is enough, also allocates space via new char[sz].

`int present = a.contains(void* ptr)`
: returns true if ptr is held in one of the ring entries.

`a.clear()`
: deletes all space pointed to in any entry. This is called automatically upon destruction.

`a.free(void* ptr)`
: If ptr is one of the entries, calls delete of the pointer, and resets to entry pointer to null.

17 The String class

The `String` class is designed to extend GNU C++ to support string processing capabilities similar to those in languages like Awk. The class provides facilities that ought to be convenient and efficient enough to be useful replacements for `char*` based processing via the C string library (i.e., `strcpy, strcmp,` etc.) in many applications. Many details about String representations are described in the Representation section.

A separate `SubString` class supports substring extraction and modification operations. This is implemented in a way that user programs never directly construct or represent substrings, which are only used indirectly via String operations.

Another separate class, `Regex` is also used indirectly via String operations in support of regular expression searching, matching, and the like. The Regex class is based entirely on the GNU Emacs regex functions. See section "Syntax of Regular Expressions" in *GNU Emacs Manual*, for a full explanation of regular expression syntax. (For implementation details, see the internal documentation in files '`regex.h`' and '`regex.c`'.)

17.1 Constructors

Strings are initialized and assigned as in the following examples:

`String x; String y = 0; String z = "";`
: Set x, y, and z to the nil string. Note that either 0 or "" may always be used to refer to the nil string.

`String x = "Hello"; String y("Hello");`
: Set x and y to a copy of the string "Hello".

`String x = 'A'; String y('A');`
: Set x and y to the string value "A"

`String u = x; String v(x);`
: Set u and v to the same string as String x

`String u = x.at(1,4); String v(x.at(1,4));`
: Set u and v to the length 4 substring of x starting at position 1 (counting indexes from 0).

`String x("abc", 2);`
: Sets x to "ab", i.e., the first 2 characters of "abc".

`String x = dec(20);`
: Sets x to "20". As here, Strings may be initialized or assigned the results of any `char*` function.

There are no directly accessible forms for declaring SubString variables.

The declaration `Regex r("[a-zA-Z_][a-zA-Z0-9_]*");` creates a compiled regular expression suitable for use in String operations described below. (In this case, one that matches any C++ identifier). The first argument may also be a String. Be careful in distinguishing the role of backslashes in quoted GNU C++ char* constants versus those in Regexes. For example, a Regex that matches either one or more tabs or all strings beginning with

"ba" and ending with any number of occurrences of "na" could be declared as `Regex r = "\\(\t+\\)\\|\\(ba\\(na\\)*\\)"` Note that only one backslash is needed to signify the tab, but two are needed for the parenthesization and virgule, since the GNU C++ lexical analyzer decodes and strips backslashes before they are seen by Regex.

There are three additional optional arguments to the Regex constructor that are less commonly useful:

`fast (default 0)`
: `fast` may be set to true (1) if the Regex should be "fast-compiled". This causes an additional compilation step that is generally worthwhile if the Regex will be used many times.

`bufsize (default max(40, length of the string))`
: This is an estimate of the size of the internal compiled expression. Set it to a larger value if you know that the expression will require a lot of space. If you do not know, do not worry: realloc is used if necessary.

`transtable (default none == 0)`
: The address of a byte translation table (a char[256]) that translates each character before matching.

As a convenience, several Regexes are predefined and usable in any program. Here are their declarations from '`String.h`'.

```
extern Regex RXwhite;      // = "[ \n\t]+"
extern Regex RXint;        // = "-?[0-9]+"
extern Regex RXdouble;     // = "-?\\(\\([0-9]+\\.[0-9]*\\)\\|
                           //    \\([0-9]+\\)\\|
                           //    \\(\\.[0-9]+\\)\\)
                           //    \\([eE][---+]?[0-9]+\\)?"
extern Regex RXalpha;      // = "[A-Za-z]+"
extern Regex RXlowercase;  // = "[a-z]+"
extern Regex RXuppercase;  // = "[A-Z]+"
extern Regex RXalphanum;   // = "[0-9A-Za-z]+"
extern Regex RXidentifier; // = "[A-Za-z_][A-Za-z0-9_]*"
```

17.2 Examples

Most `String` class capabilities are best shown via example. The examples below use the following declarations.

```
String x = "Hello";
String y = "world";
String n = "123";
String z;
char*  s = ",";
String lft, mid, rgt;
Regex  r = "e[a-z]*o";
Regex  r2("/[a-z]*/");
char   c;
```

```
int    i, pos, len;
double f;
String words[10];
words[0] = "a";
words[1] = "b";
words[2] = "c";
```

17.3 Comparing, Searching and Matching

The usual lexicographic relational operators (`==, !=, <, <=, >, >=`) are defined. A functional form `compare(String, String)` is also provided, as is `fcompare(String, String)`, which compares Strings without regard for upper vs. lower case.

All other matching and searching operations are based on some form of the (non-public) `match` and `search` functions. `match` and `search` differ in that `match` attempts to match only at the given starting position, while `search` starts at the position, and then proceeds left or right looking for a match. As seen in the following examples, the second optional `startpos` argument to functions using `match` and `search` specifies the starting position of the search: If non-negative, it results in a left-to-right search starting at position `startpos`, and if negative, a right-to-left search starting at position `x.length() + startpos`. In all cases, the index returned is that of the beginning of the match, or -1 if there is no match.

Three String functions serve as front ends to `search` and `match`. `index` performs a search, returning the index, `matches` performs a match, returning nonzero (actually, the length of the match) on success, and `contains` is a boolean function performing either a search or match, depending on whether an index argument is provided:

`x.index("lo")`
: returns the zero-based index of the leftmost occurrence of substring "lo" (3, in this case). The argument may be a String, SubString, char, char*, or Regex.

`x.index("l", 2)`
: returns the index of the first of the leftmost occurrence of "l" found starting the search at position x[2], or 2 in this case.

`x.index("l", -1)`
: returns the index of the rightmost occurrence of "l", or 3 here.

`x.index("l", -3)`
: returns the index of the rightmost occurrence of "l" found by starting the search at the 3rd to the last position of x, returning 2 in this case.

`pos = r.search("leo", 3, len, 0)`
: returns the index of r in the `char*` string of length 3, starting at position 0, also placing the length of the match in reference parameter len.

`x.contains("He")`
: returns nonzero if the String x contains the substring "He". The argument may be a String, SubString, char, char*, or Regex.

`x.contains("el", 1)`
: returns nonzero if x contains the substring "el" at position 1. As in this example, the second argument to `contains`, if present, means to match the substring only at that position, and not to search elsewhere in the string.

`x.contains(RXwhite);`
: returns nonzero if x contains any whitespace (space, tab, or newline). Recall that `RXwhite` is a global whitespace Regex.

`x.matches("lo", 3)`
: returns nonzero if x starting at position 3 exactly matches "lo", with no trailing characters (as it does in this example).

`x.matches(r)`
: returns nonzero if String x as a whole matches Regex r.

`int f = x.freq("l")`
: returns the number of distinct, nonoverlapping matches to the argument (2 in this case).

17.4 Substring extraction

Substrings may be extracted via the `at`, `before`, `through`, `from`, and `after` functions. These behave as either lvalues or rvalues.

`z = x.at(2, 3)`
: sets String z to be equal to the length 3 substring of String x starting at zero-based position 2, setting z to "llo" in this case. A nil String is returned if the arguments don't make sense.

`x.at(2, 2) = "r"`
: Sets what was in positions 2 to 3 of x to "r", setting x to "Hero" in this case. As indicated here, SubString assignments may be of different lengths.

`x.at("He") = "je";`
: x("He") is the substring of x that matches the first occurrence of it's argument. The substitution sets x to "jello". If "He" did not occur, the substring would be nil, and the assignment would have no effect.

`x.at("l", -1) = "i";`
: replaces the rightmost occurrence of "l" with "i", setting x to "Helio".

`z = x.at(r)`
: sets String z to the first match in x of Regex r, or "ello" in this case. A nil String is returned if there is no match.

`z = x.before("o")`
: sets z to the part of x to the left of the first occurrence of "o", or "Hell" in this case. The argument may also be a String, SubString, or Regex. (If there is no match, z is set to "".)

`x.before("ll") = "Bri";`
: sets the part of x to the left of "ll" to "Bri", setting x to "Brillo".

`z = x.before(2)`
: sets z to the part of x to the left of x[2], or "He" in this case.

`z = x.after("Hel")`
: sets z to the part of x to the right of "Hel", or "lo" in this case.

`z = x.through("el")`
: sets z to the part of x up and including "el", or "Hel" in this case.

`z = x.from("el")`
: sets z to the part of x from "el" to the end, or "ello" in this case.

`x.after("Hel") = "p";`
: sets x to "Help";

`z = x.after(3)`
: sets z to the part of x to the right of x[3] or "o" in this case.

`z = " ab c"; z = z.after(RXwhite)`
: sets z to the part of its old string to the right of the first group of whitespace, setting z to "ab c"; Use gsub(below) to strip out multiple occurrences of whitespace or any pattern.

`x[0] = 'J';`
: sets the first element of x to 'J'. x[i] returns a reference to the ith element of x, or triggers an error if i is out of range.

`common_prefix(x, "Help")`
: returns the String containing the common prefix of the two Strings or "Hel" in this case.

`common_suffix(x, "to")`
: returns the String containing the common suffix of the two Strings or "o" in this case.

17.5 Concatenation

`z = x + s + ' ' + y.at("w") + y.after("w") + ".";`
: sets z to "Hello, world."

`x += y;` sets x to "Helloworld"

`cat(x, y, z)`
: A faster way to say z = x + y.

`cat(z, y, x, x)`
: Double concatenation; A faster way to say x = z + y + x.

`y.prepend(x);`
: A faster way to say y = x + y.

`z = replicate(x, 3);`
: sets z to "HelloHelloHello".

`z = join(words, 3, "/")`
: sets z to the concatenation of the first 3 Strings in String array words, each separated by "/", setting z to "a/b/c" in this case. The last argument may be "" or 0, indicating no separation.

17.6 Other manipulations

`z = "this string has five words"; i = split(z, words, 10, RXwhite);`
: sets up to 10 elements of String array words to the parts of z separated by whitespace, and returns the number of parts actually encountered (5 in this case). Here, words[0] = "this", words[1] = "string", etc. The last argument may be any of the usual. If there is no match, all of z ends up in words[0]. The words array is *not* dynamically created by split.

`int nmatches x.gsub("l","ll")`
: substitutes all original occurrences of "l" with "ll", setting x to "Hellllo". The first argument may be any of the usual, including Regex. If the second argument is "" or 0, all occurrences are deleted. gsub returns the number of matches that were replaced.

`z = x + y; z.del("loworl");`
: deletes the leftmost occurrence of "loworl" in z, setting z to "Held".

`z = reverse(x)`
: sets z to the reverse of x, or "olleH".

`z = upcase(x)`
: sets z to x, with all letters set to uppercase, setting z to "HELLO"

`z = downcase(x)`
: sets z to x, with all letters set to lowercase, setting z to "hello"

`z = capitalize(x)`
: sets z to x, with the first letter of each word set to uppercase, and all others to lowercase, setting z to "Hello"

`x.reverse(), x.upcase(), x.downcase(), x.capitalize()`
: in-place, self-modifying versions of the above.

17.7 Reading, Writing and Conversion

`cout << x` writes out x.

`cout << x.at(2, 3)`
: writes out the substring "llo".

`cin >> x` reads a whitespace-bounded string into x.

`x.length()`
: returns the length of String x (5, in this case).

`s = (const char*)x`

can be used to extract the `char*` char array. This coercion is useful for sending a String as an argument to any function expecting a `const char*` argument (like `atoi`, and `File::open`). This operator must be used with care, since the conversion returns a pointer to `String` internals without copying the characters: The resulting `(char*)` is only valid until the next String operation, and you must not modify it. (The conversion is defined to return a const value so that GNU C++ will produce warning and/or error messages if changes are attempted.)

18 The Integer class.

The `Integer` class provides multiple precision integer arithmetic facilities. Some representation details are discussed in the Representation section.

`Integers` may be up to `b * ((1 << b) - 1)` bits long, where `b` is the number of bits per short (typically 1048560 bits when `b = 16`). The implementation assumes that a `long` is at least twice as long as a `short`. This assumption hides beneath almost all primitive operations, and would be very difficult to change. It also relies on correct behavior of *unsigned* arithmetic operations.

Some of the arithmetic algorithms are very loosely based on those provided in the MIT Scheme '`bignum.c`' release, which is Copyright (c) 1987 Massachusetts Institute of Technology. Their use here falls within the provisions described in the Scheme release.

Integers may be constructed in the following ways:

`Integer x;`
: Declares an uninitialized Integer.

`Integer x = 2; Integer y(2);`
: Set x and y to the Integer value 2;

`Integer u(x); Integer v = x;`
: Set u and v to the same value as x.

`long` **Integer::as_long**() `const` Method
: Used to coerce an `Integer` back into longs via the `long` coercion operator. If the Integer cannot fit into a long, this returns MINLONG or MAXLONG (depending on the sign) where MINLONG is the most negative, and MAXLONG is the most positive representable long.

`int` **Integer::fits_in_long**() `const` Method
: Returns true iff the `Integer` is `< MAXLONG` and `> MINLONG`.

`double` **Integer::as_double**() `const` Method
: Coerce the `Integer` to a `double`, with potential loss of precision. `+/-HUGE` is returned if the Integer cannot fit into a double.

`int` **Integer::fits_in_double**() `const` Method
: Returns true iff the `Integer` can fit into a double.

All of the usual arithmetic operators are provided (`+, -, *, /, %, +=, ++, -=, --, *=, /=, %=, ==, !=, <, <=, >, >=`). All operators support special versions for mixed arguments of Integers and regular C++ longs in order to avoid useless coercions, as well as to allow automatic promotion of shorts and ints to longs, so that they may be applied without additional Integer coercion operators. The only operators that behave differently than the corresponding int or long operators are `++` and `--`. Because C++ does not distinguish prefix from postfix application, these are declared as `void` operators, so that no confusion can result from applying them as postfix. Thus, for Integers x and y, `++x; y = x;` is correct, but `y = ++x;` and `y = x++;` are not.

Bitwise operators (`~`, `&`, `|`, `^`, `<<`, `>>`, `&=`, `|=`, `^=`, `<<=`, `>>=`) are also provided. However, these operate on sign-magnitude, rather than two's complement representations. The sign of the result is arbitrarily taken as the sign of the first argument. For example, `Integer(-3) & Integer(5)` returns `Integer(-1)`, not -3, as it would using two's complement. Also, `~`, the complement operator, complements only those bits needed for the representation. Bit operators are also provided in the BitSet and BitString classes. One of these classes should be used instead of Integers when the results of bit manipulations are not interpreted numerically.

The following utility functions are also provided. (All arguments are Integers unless otherwise noted).

`void` **divide(const** `Integer&` *x*, `const Integer&` *y*, `Integer&` *q*, `Integer&` *r*) — Function

Sets *q* to the quotient and *r* to the remainder of *x* and *y*. (*q* and *r* are returned by reference).

`Integer` **pow(const** `Integer&` *x*, `const Integer&` *p*) — Function

Returns *x* raised to the power *p*.

`Integer` **lpow(long** *x*, `long` *p*) — Function

Returns *x* raised to the power *p*.

`Integer` **gcd(const** `Integer&` *x*, `const Integer&` *p*) — Function

Returns the greatest common divisor of *x* and *y*.

`Integer` **lcm(const** `Integer&` *x*, `const Integer&` *p*) — Function

Returns the least common multiple of *x* and *y*.

`Integer` **abs(const** `Integer&` *x* — Function

Returns the absolute value of *x*.

`void` **Integer::negate()** — Method

Negates `this` in place.

`Integer sqr(x)`

returns x * x;

`Integer sqrt(x)`

returns the floor of the square root of x.

`long lg(x);`

returns the floor of the base 2 logarithm of abs(x)

`int sign(x)`

returns -1 if x is negative, 0 if zero, else +1. Using `if (sign(x) == 0)` is a generally faster method of testing for zero than using relational operators.

`int even(x)`

returns true if x is an even number

`int odd(x)`

returns true if x is an odd number.

`void setbit(Integer& x, long b)`
: sets the b'th bit (counting right-to-left from zero) of x to 1.

`void clearbit(Integer& x, long b)`
: sets the b'th bit of x to 0.

`int testbit(Integer x, long b)`
: returns true if the b'th bit of x is 1.

`Integer atoI(char* asciinumber, int base = 10);`
: converts the base base char* string into its Integer form.

`void Integer::printon(ostream& s, int base = 10, int width = 0);`
: prints the ascii string value of `(*this)` as a base `base` number, in field width at least `width`.

`ostream << x;`
: prints x in base ten format.

`istream >> x;`
: reads x as a base ten number.

`int compare(Integer x, Integer y)`
: returns a negative number if x<y, zero if x==y, or positive if x>y.

`int ucompare(Integer x, Integer y)`
: like compare, but performs unsigned comparison.

`add(x, y, z)`
: A faster way to say z = x + y.

`sub(x, y, z)`
: A faster way to say z = x - y.

`mul(x, y, z)`
: A faster way to say z = x * y.

`div(x, y, z)`
: A faster way to say z = x / y.

`mod(x, y, z)`
: A faster way to say z = x % y.

`and(x, y, z)`
: A faster way to say z = x & y.

`or(x, y, z)`
: A faster way to say z = x | y.

`xor(x, y, z)`
: A faster way to say z = x ^ y.

`lshift(x, y, z)`
: A faster way to say z = x << y.

`rshift(x, y, z)`
: A faster way to say z = x >> y.

`pow(x, y, z)`
: A faster way to say z = pow(x, y).

`complement(x, z)`
: A faster way to say z = ~x.

`negate(x, z)`
: A faster way to say z = -x.

19 The Rational Class

Class `Rational` provides multiple precision rational number arithmetic. All rationals are maintained in simplest form (i.e., with the numerator and denominator relatively prime, and with the denominator strictly positive). Rational arithmetic and relational operators are provided (`+, -, *, /, +=, -=, *=, /=, ==, !=, <, <=, >, >=`). Operations resulting in a rational number with zero denominator trigger an exception.

Rationals may be constructed and used in the following ways:

`Rational x;`
: Declares an uninitialized Rational.

`Rational x = 2; Rational y(2);`
: Set x and y to the Rational value 2/1;

`Rational x(2, 3);`
: Sets x to the Rational value 2/3;

`Rational x = 1.2;`
: Sets x to a Rational value close to 1.2. Any double precision value may be used to construct a Rational. The Rational will possess exactly as much precision as the double. Double values that do not have precise floating point equivalents (like 1.2) produce similarly imprecise rational values.

`Rational x(Integer(123), Integer(4567));`
: Sets x to the Rational value 123/4567.

`Rational u(x); Rational v = x;`
: Set u and v to the same value as x.

`double(Rational x)`
: A Rational may be coerced to a double with potential loss of precision. +/- HUGE is returned if it will not fit.

`Rational abs(x)`
: returns the absolute value of x.

`void x.negate()`
: negates x.

`void x.invert()`
: sets x to 1/x.

`int sign(x)`
: returns 0 if x is zero, 1 if positive, and -1 if negative.

`Rational sqr(x)`
: returns x * x.

`Rational pow(x, Integer y)`
: returns x to the y power.

`Integer x.numerator()`
: returns the numerator.

`Integer x.denominator()`
: returns the denominator.

`Integer floor(x)`
: returns the greatest Integer less than x.

`Integer ceil(x)`
: returns the least Integer greater than x.

`Integer trunc(x)`
: returns the Integer part of x.

`Integer round(x)`
: returns the nearest Integer to x.

`int compare(x, y)`
: returns a negative, zero, or positive number signifying whether x is less than, equal to, or greater than y.

`ostream << x;`
: prints x in the form num/den, or just num if the denominator is one.

`istream >> x;`
: reads x in the form num/den, or just num in which case the denominator is set to one.

`add(x, y, z)`
: A faster way to say z = x + y.

`sub(x, y, z)`
: A faster way to say z = x - y.

`mul(x, y, z)`
: A faster way to say z = x * y.

`div(x, y, z)`
: A faster way to say z = x / y.

`pow(x, y, z)`
: A faster way to say z = pow(x, y).

`negate(x, z)`
: A faster way to say z = -x.

20 The Complex class.

Class `Complex` is implemented in a way similar to that described by Stroustrup. In keeping with libg++ conventions, the class is named `Complex`, not `complex`. Complex arithmetic and relational operators are provided (`+, -, *, /, +=, -=, *=, /=, ==, !=`). Attempted division by (0, 0) triggers an exception.

Complex numbers may be constructed and used in the following ways:

`Complex x;`
: Declares an uninitialized Complex.

`Complex x = 2; Complex y(2.0);`
: Set x and y to the Complex value (2.0, 0.0);

`Complex x(2, 3);`
: Sets x to the Complex value (2, 3);

`Complex u(x); Complex v = x;`
: Set u and v to the same value as x.

`double real(Complex& x);`
: returns the real part of x.

`double imag(Complex& x);`
: returns the imaginary part of x.

`double abs(Complex& x);`
: returns the magnitude of x.

`double norm(Complex& x);`
: returns the square of the magnitude of x.

`double arg(Complex& x);`
: returns the argument (amplitude) of x.

`Complex polar(double r, double t = 0.0);`
: returns a Complex with abs of r and arg of t.

`Complex conj(Complex& x);`
: returns the complex conjugate of x.

`Complex cos(Complex& x);`
: returns the complex cosine of x.

`Complex sin(Complex& x);`
: returns the complex sine of x.

`Complex cosh(Complex& x);`
: returns the complex hyperbolic cosine of x.

`Complex sinh(Complex& x);`
: returns the complex hyperbolic sine of x.

`Complex exp(Complex& x);`
: returns the exponential of x.

`Complex log(Complex& x);`
: returns the natural log of x.

`Complex pow(Complex& x, long p);`
: returns x raised to the p power.

`Complex pow(Complex& x, Complex& p);`
: returns x raised to the p power.

`Complex sqrt(Complex& x);`
: returns the square root of x.

`ostream << x;`
: prints x in the form (re, im).

`istream >> x;`
: reads x in the form (re, im), or just (re) or re in which case the imaginary part is set to zero.

21 Fixed precision numbers

Classes `Fix16`, `Fix24`, `Fix32`, and `Fix48` support operations on 16, 24, 32, or 48 bit quantities that are considered as real numbers in the range [-1, +1). Such numbers are often encountered in digital signal processing applications. The classes may be be used in isolation or together. Class `Fix32` operations are entirely self-contained. Class `Fix16` operations are self-contained except that the multiplication operation `Fix16 * Fix16` returns a `Fix32`. `Fix24` and `Fix48` are similarly related.

The standard arithmetic and relational operations are supported (`=`, `+`, `-`, `*`, `/`, `<<`, `>>`, `+=`, `-=`, `*=`, `/=`, `<<=`, `>>=`, `==`, `!=`, `<`, `<=`, `>`, `>=`). All operations include provisions for special handling in cases where the result exceeds +/- 1.0. There are two cases that may be handled separately: "overflow" where the results of addition and subtraction operations go out of range, and all other "range errors" in which resulting values go off-scale (as with division operations, and assignment or initialization with off-scale values). In signal processing applications, it is often useful to handle these two cases differently. Handlers take one argument, a reference to the integer mantissa of the offending value, which may then be manipulated. In cases of overflow, this value is the result of the (integer) arithmetic computation on the mantissa; in others it is a fully saturated (i.e., most positive or most negative) value. Handling may be reset to any of several provided functions or any other user-defined function via `set_overflow_handler` and `set_range_error_handler`. The provided functions for `Fix16` are as follows (corresponding functions are also supported for the others).

`Fix16_overflow_saturate`
: The default overflow handler. Results are "saturated": positive results are set to the largest representable value (binary 0.111111...), and negative values to -1.0.

`Fix16_ignore`
: Performs no action. For overflow, this will allow addition and subtraction operations to "wrap around" in the same manner as integer arithmetic, and for saturation, will leave values saturated.

`Fix16_overflow_warning_saturate`
: Prints a warning message on standard error, then saturates the results.

`Fix16_warning`
: The default range_error handler. Prints a warning message on standard error; otherwise leaving the argument unmodified.

`Fix16_abort`
: prints an error message on standard error, then aborts execution.

In addition to arithmetic operations, the following are provided:

`Fix16 a = 0.5;`
: Constructs fixed precision objects from double precision values. Attempting to initialize to a value outside the range invokes the range_error handler, except, as a convenience, initialization to 1.0 sets the variable to the most positive representable value (binary 0.1111111...) without invoking the handler.

`short& mantissa(a); long& mantissa(b);`
: return a * pow(2, 15) or b * pow(2, 31) as an integer. These are returned by reference, to enable "manual" data manipulation.

`double value(a); double value(b);`
: return a or b as floating point numbers.

22 Classes for Bit manipulation

libg++ provides several different classes supporting the use and manipulation of collections of bits in different ways.

- Class `Integer` provides "integer" semantics. It supports manipulation of bits in ways that are often useful when treating bit arrays as numerical (integer) quantities. This class is described elsewhere.
- Class `BitSet` provides "set" semantics. It supports operations useful when treating collections of bits as representing potentially infinite sets of integers.
- Class `BitSet32` supports fixed-length BitSets holding exactly 32 bits.
- Class `BitSet256` supports fixed-length BitSets holding exactly 256 bits.
- Class `BitString` provides "string" (or "vector") semantics. It supports operations useful when treating collections of bits as strings of zeros and ones.

These classes also differ in the following ways:

- BitSets are logically infinite. Their space is dynamically altered to adjust to the smallest number of consecutive bits actually required to represent the sets. Integers also have this property. BitStrings are logically finite, but their sizes are internally dynamically managed to maintain proper length. This means that, for example, BitStrings are concatenatable while BitSets and Integers are not.
- BitSet32 and BitSet256 have precisely the same properties as BitSets, except that they use constant fixed length bit vectors.
- While all classes support basic unary and binary operations `~`, `&`, `|`, `^`, `-`, the semantics differ. BitSets perform bit operations that precisely mirror those for infinite sets. For example, complementing an empty BitSet returns one representing an infinite number of set bits. Operations on BitStrings and Integers operate only on those bits actually present in the representation. For BitStrings and Integers, the the `&` operation returns a BitString with a length equal to the minimum length of the operands, and `|`, `^` return one with length of the maximum.
- Only BitStrings support substring extraction and bit pattern matching.

22.1 BitSet

BitSets are objects that contain logically infinite sets of nonnegative integers. Representational details are discussed in the Representation chapter. Because they are logically infinite, all BitSets possess a trailing, infinitely replicated 0 or 1 bit, called the "virtual bit", and indicated via 0* or 1*.

BitSet32 and BitSet256 have they same properties, except they are of fixed length, and thus have no virtual bit.

BitSets may be constructed as follows:

`BitSet a;` declares an empty BitSet.

`BitSet a = atoBitSet("001000");`
sets a to the BitSet 0010*, reading left-to-right. The "0*" indicates that the set ends with an infinite number of zero (clear) bits.

`BitSet a = atoBitSet("00101*");`
sets a to the BitSet 00101*, where "1*" means that the set ends with an infinite number of one (set) bits.

`BitSet a = longtoBitSet((long)23);`
sets a to the BitSet 111010*, the binary representation of decimal 23.

`BitSet a = utoBitSet((unsigned)23);`
sets a to the BitSet 111010*, the binary representation of decimal 23.

The following functions and operators are provided (Assume the declaration of BitSets a = 0011010*, b = 101101*, throughout, as examples).

`~a` returns the complement of a, or 1100101* in this case.

`a.complement()`
sets a to ~a.

`a & b; a &= b;`
returns a intersected with b, or 0011010*.

`a | b; a |= b;`
returns a unioned with b, or 1011111*.

`a - b; a -= b;`
returns the set difference of a and b, or 000010*.

`a ^ b; a ^= b;`
returns the symmetric difference of a and b, or 1000101*.

`a.empty()`
returns true if a is an empty set.

`a == b;` returns true if a and b contain the same set.

`a <= b;` returns true if a is a subset of b.

`a < b;` returns true if a is a proper subset of b;

`a != b; a >= b; a > b;`
are the converses of the above.

`a.set(7)` sets the 7th (counting from 0) bit of a, setting a to 001111010*

`a.clear(2)`
clears the 2nd bit bit of a, setting a to 00011110*

`a.clear()`
clears all bits of a;

`a.set()` sets all bits of a;

`a.invert(0)`
complements the 0th bit of a, setting a to 10011110*

`a.set(0,1)`
sets the 0th through 1st bits of a, setting a to 110111110* The two-argument versions of clear and invert are similar.

`a.test(3)`
: returns true if the 3rd bit of a is set.

`a.test(3, 5)`
: returns true if any of bits 3 through 5 are set.

`int i = a[3]; a[3] = 0;`
: The subscript operator allows bits to be inspected and changed via standard subscript semantics, using a friend class BitSetBit. The use of the subscript operator a[i] rather than a.test(i) requires somewhat greater overhead.

`a.first(1)` or `a.first()`
: returns the index of the first set bit of a (2 in this case), or -1 if no bits are set.

`a.first(0)`
: returns the index of the first clear bit of a (0 in this case), or -1 if no bits are clear.

`a.next(2, 1)` or `a.next(2)`
: returns the index of the next bit after position 2 that is set (3 in this case) or -1. `first` and `next` may be used as iterators, as in `for (int i = a.first(); i >= 0; i = a.next(i))...`.

`a.last(1)`
: returns the index of the rightmost set bit, or -1 if there or no set bits or all set bits.

`a.prev(3, 0)`
: returns the index of the previous clear bit before position 3.

`a.count(1)`
: returns the number of set bits in a, or -1 if there are an infinite number.

`a.virtual_bit()`
: returns the trailing (infinitely replicated) bit of a.

`a = atoBitSet("ababX", 'a', 'b', 'X');`
: converts the char* string into a bitset, with 'a' denoting false, 'b' denoting true, and 'X' denoting infinite replication.

`a.printon(cout, '-', '.', 0)`
: prints `a` to `cout` represented with `'-'` for falses, `'.'` for trues, and no replication marker.

`cout << a` prints `a` to `cout` (representing lases by `'f'`, trues by `'t'`, and using `'*'` as the replication marker).

`diff(x, y, z)`
: A faster way to say z = x - y.

`and(x, y, z)`
: A faster way to say z = x & y.

`or(x, y, z)`
: A faster way to say z = x | y.

`xor(x, y, z)`
: A faster way to say z = x ^ y.

`complement(x, z)`
: A faster way to say z = ~x.

22.2 BitString

BitStrings are objects that contain arbitrary-length strings of zeroes and ones. BitStrings possess some features that make them behave like sets, and others that behave as strings. They are useful in applications (such as signature-based algorithms) where both capabilities are needed. Representational details are discussed in the Representation chapter. Most capabilities are exact analogs of those supported in the BitSet and String classes. A BitSubString is used with substring operations along the same lines as the String SubString class. A BitPattern class is used for masked bit pattern searching.

Only a default constructor is supported. The declaration `BitString a;` initializes a to be an empty BitString. BitStrings may often be initialized via `atoBitString` and `longtoBitString`.

Set operations (`~, complement, &, &=, |, |=, -, ^, ^=`) behave just as the BitSet versions, except that there is no "virtual bit": complementing complements only those bits in the BitString, and all binary operations across unequal length BitStrings assume a virtual bit of zero. The `&` operation returns a BitString with a length equal to the minimum length of the operands, and `|, ^` return one with length of the maximum.

Set-based relational operations (`==, !=, <=, <, >=, >`) follow the same rules. A string-like lexicographic comparison function, `lcompare`, tests the lexicographic relation between two BitStrings. For example, lcompare(1100, 0101) returns 1, since the first BitString starts with 1 and the second with 0.

Individual bit setting, testing, and iterator operations (`set, clear, invert, test, first, next, last, prev`) are also like those for BitSets. BitStrings are automatically expanded when setting bits at positions greater than their current length.

The string-based capabilities are just as those for class String. BitStrings may be concatenated (`+, +=`), searched (`index, contains, matches`), and extracted into BitSubStrings (`before, at, after`) which may be assigned and otherwise manipulated. Other string-based utility functions (`reverse, common_prefix, common_suffix`) are also provided. These have the same capabilities and descriptions as those for Strings.

String-oriented operations can also be performed with a mask via class BitPattern. BitPatterns consist of two BitStrings, a pattern and a mask. On searching and matching, bits in the pattern that correspond to 0 bits in the mask are ignored. (The mask may be shorter than the pattern, in which case trailing mask bits are assumed to be 0). The pattern and mask are both public variables, and may be individually subjected to other bit operations.

Converting to char* and printing (`(atoBitString, atoBitPattern, printon, ostream <<)`) are also as in BitSets, except that no virtual bit is used, and an 'X' in a BitPattern means that the pattern bit is masked out.

The following features are unique to BitStrings.

Assume declarations of BitString a = atoBitString("01010110") and b = atoBitSTring("1101").

`a = b + c;` Sets a to the concatenation of b and c;

`a = b + 0; a = b + 1;`
sets a to b, appended with a zero (one).

`a += b;` appends b to a;

`a += 0; a += 1;`
appends a zero (one) to a.

`a << 2; a <<= 2`
return a with 2 zeros prepended, setting a to 0001010110. (Note the necessary confusion of `<<` and `>>` operators. For consistency with the integer versions, `<<` shifts low bits to high, even though they are printed low bits first.)

`a >> 3; a >>= 3`
return a with the first 3 bits deleted, setting a to 10110.

`a.left_trim(0)`
deletes all 0 bits on the left of a, setting a to 1010110.

`a.right_trim(0)`
deletes all trailing 0 bits of a, setting a to 0101011.

`cat(x, y, z)`
A faster way to say z = x + y.

`diff(x, y, z)`
A faster way to say z = x - y.

`and(x, y, z)`
A faster way to say z = x & y.

`or(x, y, z)`
A faster way to say z = x | y.

`xor(x, y, z)`
A faster way to say z = x ^ y.

`lshift(x, y, z)`
A faster way to say z = x << y.

`rshift(x, y, z)`
A faster way to say z = x >> y.

`complement(x, z)`
A faster way to say z = ~x.

23 Random Number Generators and related classes

The two classes `RNG` and `Random` are used together to generate a variety of random number distributions. A distinction must be made between *random number generators*, implemented by class `RNG`, and *random number distributions*. A random number generator produces a series of randomly ordered bits. These bits can be used directly, or cast to other representations, such as a floating point value. A random number generator should produce a *uniform* distribution. A random number distribution, on the other hand, uses the randomly generated bits of a generator to produce numbers from a distribution with specific properties. Each instance of `Random` uses an instance of class `RNG` to provide the raw, uniform distribution used to produce the specific distribution. Several instances of `Random` classes can share the same instance of `RNG`, or each instance can use its own copy.

23.1 RNG

Random distributions are constructed from members of class `RNG`, the actual random number generators. The `RNG` class contains no data; it only serves to define the interface to random number generators. The `RNG::asLong` member returns an unsigned long (typically 32 bits) of random bits. Applications that require a number of random bits can use this directly. More often, these random bits are transformed to a uniform random number:

```
        //
        // Return random bits converted to either a float or a double
        //
        float asFloat();
        double asDouble();
    };
```

using either `asFloat` or `asDouble`. It is intended that `asFloat` and `asDouble` return differing precisions; typically, `asDouble` will draw two random longwords and transform them into a legal `double`, while `asFloat` will draw a single longword and transform it into a legal `float`. These members are used by subclasses of the `Random` class to implement a variety of random number distributions.

23.2 ACG

Class `ACG` is a variant of a Linear Congruential Generator (Algorithm M) described in Knuth, *Art of Computer Programming, Vol III*. This result is permuted with a Fibonacci Additive Congruential Generator to get good independence between samples. This is a very high quality random number generator, although it requires a fair amount of memory for each instance of the generator.

The `ACG::ACG` constructor takes two parameters: the seed and the size. The seed is any number to be used as an initial seed. The performance of the generator depends on having a distribution of bits through the seed. If you choose a number in the range of 0 to 31, a seed with more bits is chosen. Other values are deterministically modified to give a better distribution of bits. This provides a good random number generator while still allowing a sequence to be repeated given the same initial seed.

The `size` parameter determines the size of two tables used in the generator. The first table is used in the Additive Generator; see the algorithm in Knuth for more information. In general, this table is `size` longwords long. The default value, used in the algorithm in Knuth, gives a table of 220 bytes. The table size affects the period of the generators; smaller values give shorter periods and larger tables give longer periods. The smallest table size is 7 longwords, and the longest is 98 longwords. The `size` parameter also determines the size of the table used for the Linear Congruential Generator. This value is chosen implicitly based on the size of the Additive Congruential Generator table. It is two powers of two larger than the power of two that is larger than `size`. For example, if `size` is 7, the ACG table is 7 longwords and the LCG table is 128 longwords. Thus, the default size (55) requires 55 + 256 longwords, or 1244 bytes. The largest table requires 2440 bytes and the smallest table requires 100 bytes. Applications that require a large number of generators or applications that aren't so fussy about the quality of the generator may elect to use the `MLCG` generator.

23.3 MLCG

The `MLCG` class implements a *Multiplicative Linear Congruential Generator*. In particular, it is an implementation of the double MLCG described in *"Efficient and Portable Combined Random Number Generators"* by Pierre L'Ecuyer, appearing in *Communications of the ACM, Vol. 31. No. 6.* This generator has a fairly long period, and has been statistically analyzed to show that it gives good inter-sample independence.

The `MLCG::MLCG` constructor has two parameters, both of which are seeds for the generator. As in the `MLCG` generator, both seeds are modified to give a "better" distribution of seed digits. Thus, you can safely use values such as '0' or '1' for the seeds. The `MLCG` generator used much less state than the `ACG` generator; only two longwords (8 bytes) are needed for each generator.

23.4 Random

A random number generator may be declared by first declaring a `RNG` and then a `Random`. For example, `ACG gen(10, 20); NegativeExpntl rnd (1.0, &gen);` declares an additive congruential generator with seed 10 and table size 20, that is used to generate exponentially distributed values with mean of 1.0.

The virtual member `Random::operator()` is the common way of extracting a random number from a particular distribution. The base class, `Random` does not implement `operator()`. This is performed by each of the subclasses. Thus, given the above declaration of `rnd`, new random values may be obtained via, for example, `double next_exp_rand = rnd();` Currently, the following subclasses are provided.

23.5 Binomial

The binomial distribution models successfully drawing items from a pool. The first parameter to the constructor, `n`, is the number of items in the pool, and the second parameter, `u`, is the probability of each item being successfully drawn. The member `asDouble` returns the number of samples drawn from the pool. Although it is not checked, it is assumed that `n>0` and `0 <= u <= 1`. The remaining members allow you to read and set the parameters.

23.6 Erlang

The `Erlang` class implements an Erlang distribution with mean `mean` and variance `variance`.

23.7 Geometric

The `Geometric` class implements a discrete geometric distribution. The first parameter to the constructor, `mean`, is the mean of the distribution. Although it is not checked, it is assumed that `0 <= mean <= 1`. `Geometric()` returns the number of uniform random samples that were drawn before the sample was larger than `mean`. This quantity is always greater than zero.

23.8 HyperGeometric

The `HyperGeometric` class implements the hypergeometric distribution. The first parameter to the constructor, `mean`, is the mean and the second, `variance`, is the variance. The remaining members allow you to inspect and change the mean and variance.

23.9 NegativeExpntl

The `NegativeExpntl` class implements the negative exponential distribution. The first parameter to the constructor is the mean. The remaining members allow you to inspect and change the mean.

23.10 Normal

The `Normal`class implements the normal distribution. The first parameter to the constructor, `mean`, is the mean and the second, `variance`, is the variance. The remaining members allow you to inspect and change the mean and variance. The `LogNormal` class is a subclass of `Normal`.

23.11 LogNormal

The `LogNormal`class implements the logarithmic normal distribution. The first parameter to the constructor, `mean`, is the mean and the second, `variance`, is the variance. The remaining members allow you to inspect and change the mean and variance. The `LogNormal` class is a subclass of `Normal`.

23.12 Poisson

The `Poisson` class implements the poisson distribution. The first parameter to the constructor is the mean. The remaining members allow you to inspect and change the mean.

23.13 DiscreteUniform

The `DiscreteUniform` class implements a uniform random variable over the closed interval ranging from `[low..high]`. The first parameter to the constructor is `low`, and the second is `high`, although the order of these may be reversed. The remaining members allow you to inspect and change `low` and `high`.

23.14 Uniform

The `Uniform` class implements a uniform random variable over the open interval ranging from `[low..high)`. The first parameter to the constructor is `low`, and the second is `high`, although the order of these may be reversed. The remaining members allow you to inspect and change `low` and `high`.

23.15 Weibull

The `Weibull` class implements a weibull distribution with parameters `alpha` and `beta`. The first parameter to the class constructor is `alpha`, and the second parameter is `beta`. The remaining members allow you to inspect and change `alpha` and `beta`.

23.16 RandomInteger

The `RandomInteger` class is *not* a subclass of Random, but a stand-alone integer-oriented class that is dependent on the RNG classes. RandomInteger returns random integers uniformly from the closed interval `[low..high]`. The first parameter to the constructor is `low`, and the second is `high`, although both are optional. The last argument is always a generator. Additional members allow you to inspect and change `low` and `high`. Random integers are generated using `asInt()` or `asLong()`. Operator syntax (`()`) is also available as a shorthand for `asLong()`. Because `RandomInteger` is often used in simulations for which uniform random integers are desired over a variety of ranges, `asLong()` and `asInt` have `high` as an optional argument. Using this optional argument produces a single value from the new range, but does not change the default range.

24 Data Collection

Libg++ currently provides two classes for *data collection* and analysis of the collected data.

24.1 SampleStatistic

Class `SampleStatistic` provides a means of accumulating samples of `double` values and providing common sample statistics.

Assume declaration of `double x`.

`SampleStatistic a;`
: declares and initializes a.

`a.reset();`
: re-initializes a.

`a += x;` adds sample x.

`int n = a.samples();`
: returns the number of samples.

`x = a.mean;`
: returns the means of the samples.

`x = a.var()`
: returns the sample variance of the samples.

`x = a.stdDev()`
: returns the sample standard deviation of the samples.

`x = a.min()`
: returns the minimum encountered sample.

`x = a.max()`
: returns the maximum encountered sample.

`x = a.confidence(int p)`
: returns the p-percent (0 <= p < 100) confidence interval.

`x = a.confidence(double p)`
: returns the p-probability (0 <= p < 1) confidence interval.

24.2 SampleHistogram

Class `SampleHistogram` is a derived class of `SampleStatistic` that supports collection and display of samples in bucketed intervals. It supports the following in addition to `SampleStatisic` operations.

`SampleHistogram h(double lo, double hi, double width);`
: declares and initializes h to have buckets of size width from lo to hi. If the optional argument width is not specified, 10 buckets are created. The first bucket and also holds samples less than lo, and the last one holds samples greater than hi.

`int n = h.similarSamples(x)`
: returns the number of samples in the same bucket as x.

`int n = h.inBucket(int i)`
: returns the number of samples in bucket i.

`int b = h.buckets()`
: returns the number of buckets.

`h.printBuckets(ostream s)`
: prints bucket counts on ostream s.

`double bound = h.bucketThreshold(int i)`
: returns the upper bound of bucket i.

25 Curses-based classes

The `CursesWindow` class is a repackaging of standard curses library features into a class. It relies on '`curses.h`'.

The supplied '`curses.h`' is a fairly conservative declaration of curses library features, and does not include features like "screen" or X-window support. It is, for the most part, an adaptation, rather than an improvement of C-based '`curses.h`' files. The only substantive changes are the declarations of many functions as inline functions rather than macros, which was done solely to allow overloading.

The `CursesWindow` class encapsulates curses window functions within a class. Only those functions that control windows are included: Terminal control functions and macros like `cbreak` are not part of the class. All `CursesWindows` member functions have names identical to the corresponding curses library functions, except that the "w" prefix is generally dropped. Descriptions of these functions may be found in your local curses library documentation.

A `CursesWindow` may be declared via

`CursesWindow w(WINDOW* win)`
: attaches w to the existing WINDOW* win. This is constructor is normally used only in the following special case.

`CursesWindow w(stdscr)`
: attaches w to the default curses library standard screen window.

`CursesWindow w(int lines, int cols, int begin_y, int begin_x)`
: attaches to an allocated curses window with the indicated size and screen position.

`CursesWindow sub(CursesWindow& w,int l,int c,int by,int bx,char ar='a')`
: attaches to a subwindow of w created via the curses 'subwin' command. If ar is sent as 'r', the origin (by, bx) is relative to the parent window, else it is absolute.

The class maintains a static counter that is used in order to automatically call the curses library `initscr` and `endscr` functions at the proper times. These need not, and should not be called "manually".

`CursesWindows` maintain a tree of their subwindows. Upon destruction of a `CursesWindow`, all of their subwindows are also invalidated if they had not previously been destroyed.

It is possible to traverse trees of subwindows via the following member functions

`CursesWindow* w.parent()`
: returns a pointer to the parent of the subwindow, or 0 if there is none.

`CursesWindow* w.child()`
: returns the first child subwindow of the window, or 0 if there is none.

`CursesWindow* w.sibling()`
: returns the next sibling of the subwindow, or 0 if there is none.

For example, to call some function `visit` for all subwindows of a window, you could write

```
void traverse(CursesWindow& w)
{
  visit(w);
  if (w.child() != 0) traverse(*w.child);
  if (w.sibling() != 0) traverse(*w.sibling);
}
```

26 List classes

The files '`g++-include/List.hP`' and '`g++-include/List.ccP`' provide pseudo-generic Lisp-type List classes. These lists are homogeneous lists, more similar to lists in statically typed functional languages like ML than Lisp, but support operations very similar to those found in Lisp. Any particular kind of list class may be generated via the `genclass` shell command. However, the implementation assumes that the base class supports an equality operator `==`. All equality tests use the `==` operator, and are thus equivalent to the use of `equal`, not `eq` in Lisp.

All list nodes are created dynamically, and managed via reference counts. `List` variables are actually pointers to these list nodes. Lists may also be traversed via Pixes, as described in the section describing Pixes. See Chapter 9 [Pix], page 33

Supported operations are mirrored closely after those in Lisp. Generally, operations with functional forms are constructive, functional operations, while member forms (often with the same name) are sometimes procedural, possibly destructive operations.

As with Lisp, destructive operations are supported. Programmers are allowed to change head and tail fields in any fashion, creating circular structures and the like. However, again as with Lisp, some operations implicitly assume that they are operating on pure lists, and may enter infinite loops when presented with improper lists. Also, the reference-counting storage management facility may fail to reclaim unused circularly-linked nodes.

Several Lisp-like higher order functions are supported (e.g., `map`). Typedef declarations for the required functional forms are provided int the '`.h`' file.

For purposes of illustration, assume the specification of class `intList`. Common Lisp versions of supported operations are shown in brackets for comparison purposes.

26.1 Constructors and assignment

`intList a; [ (setq a nil) ]`
: Declares a to be a nil intList.

`intList b(2); [ (setq b (cons 2 nil)) ]`
: Declares b to be an intList with a head value of 2, and a nil tail.

`intList c(3, b); [ (setq c (cons 3 b)) ]`
: Declares c to be an intList with a head value of 3, and b as its tail.

`b = a; [ (setq b a) ]`
: Sets b to be the same list as a.

Assume the declarations of intLists a, b, and c in the following. See Chapter 9 [Pix], page 33.

26.2 List status

`a.null(); OR !a; [ (null a) ]`
: returns true if a is null.

`a.valid(); [ (listp a) ]`
: returns true if a is non-null. Inside a conditional test, the `void*` coercion may also be used as in `if (a) ...`.

`intList(); [ nil ]`
: intList() may be used to null terminate a list, as in `intList f(int x) {if (x == 0) return intList(); ... }` .

`a.length(); [ (length a) ]`
: returns the length of a.

`a.list_length(); [ (list-length a) ]`
: returns the length of a, or -1 if a is circular.

26.3 heads and tails

`a.get(); OR a.head() [ (car a) ]`
: returns a reference to the head field.

`a[2]; [ (elt a 2) ]`
: returns a reference to the second (counting from zero) head field.

`a.tail(); [ (cdr a) ]`
: returns the intList that is the tail of a.

`a.last(); [ (last a) ]`
: returns the intList that is the last node of a.

`a.nth(2); [ (nth a 2) ]`
: returns the intList that is the nth node of a.

`a.set_tail(b); [ (rplacd a b) ]`
: sets a's tail to b.

`a.push(2); [ (push 2 a) ]`
: equivalent to a = intList(2, a);

`int x = a.pop() [ (setq x (car a)) (pop a) ]`
: returns the head of a, also setting a to its tail.

26.4 Constructive operations

`b = copy(a); [ (setq b (copy-seq a)) ]`
: sets b to a copy of a.

`b = reverse(a); [ (setq b (reverse a)) ]`
: Sets b to a reversed copy of a.

`c = concat(a, b); [ (setq c (concat a b)) ]`
: Sets c to a concatenated copy of a and b.

`c = append(a, b); [ (setq c (append a b)) ]`
: Sets c to a concatenated copy of a and b. All nodes of a are copied, with the last node pointing to b.

`b = map(f, a); [ (setq b (mapcar f a)) ]`
Sets b to a new list created by applying function f to each node of a.

`c = combine(f, a, b);`
Sets c to a new list created by applying function f to successive pairs of a and b. The resulting list has length the shorter of a and b.

`b = remove(x, a); [ (setq b (remove x a)) ]`
Sets b to a copy of a, omitting all occurrences of x.

`b = remove(f, a); [ (setq b (remove-if f a)) ]`
Sets b to a copy of a, omitting values causing function f to return true.

`b = select(f, a); [ (setq b (remove-if-not f a)) ]`
Sets b to a copy of a, omitting values causing function f to return false.

`c = merge(a, b, f); [ (setq c (merge a b f)) ]`
Sets c to a list containing the ordered elements (using the comparison function f) of the sorted lists a and b.

26.5 Destructive operations

`a.append(b); [ (rplacd (last a) b) ]`
appends b to the end of a. No new nodes are constructed.

`a.prepend(b); [ (setq a (append b a)) ]`
prepends b to the beginning of a.

`a.del(x); [ (delete x a) ]`
deletes all nodes with value x from a.

`a.del(f); [ (delete-if f a) ]`
deletes all nodes causing function f to return true.

`a.select(f); [ (delete-if-not f a) ]`
deletes all nodes causing function f to return false.

`a.reverse(); [ (nreverse a) ]`
reverses a in-place.

`a.sort(f); [ (sort a f) ]`
sorts a in-place using ordering (comparison) function f.

`a.apply(f); [ (mapc f a) ]`
Applies void function f (int x) to each element of a.

`a.subst(int old, int repl); [ (nsubst repl old a) ]`
substitutes repl for each occurrence of old in a. Note the different argument order than the Lisp version.

26.6 Other operations

`a.find(int x); [ (find x a) ]`
: returns the intList at the first occurrence of x.

`a.find(b); [ (find b a) ]`
: returns the intList at the first occurrence of sublist b.

`a.contains(int x); [ (member x a) ]`
: returns true if a contains x.

`a.contains(b); [ (member b a) ]`
: returns true if a contains sublist b.

`a.position(int x); [ (position x a) ]`
: returns the zero-based index of x in a, or -1 if x does not occur.

`int x = a.reduce(f, int base); [ (reduce f a :initial-value base) ]`
: Accumulates the result of applying int function f(int, int) to successive elements of a, starting with base.

27 Linked Lists

SLLists provide pseudo-generic singly linked lists. DLLists provide doubly linked lists. The lists are designed for the simple maintenance of elements in a linked structure, and do not provide the more extensive operations (or node-sharing) of class `List`. They behave similarly to the `slist` and similar classes described by Stroustrup.

All list nodes are created dynamically. Assignment is performed via copying.

Class `DLList` supports all `SLList` operations, plus additional operations described below.

For purposes of illustration, assume the specification of class `intSLList`. In addition to the operations listed here, SLLists support traversal via Pixes. See Chapter 9 [Pix], page 33

`intSLList a;`
: Declares a to be an empty list.

`intSLList b = a;`
: Sets b to an element-by-element copy of a.

`a.empty()`
: returns true if a contains no elements

`a.length();`
: returns the number of elements in a.

`a.prepend(x);`
: places x at the front of the list.

`a.append(x);`
: places x at the end of the list.

`a.join(b)`
: places all nodes from b to the end of a, simultaneously destroying b.

`x = a.front()`
: returns a reference to the item stored at the head of the list, or triggers an error if the list is empty.

`a.rear()` returns a reference to the rear of the list, or triggers an error if the list is empty.

`x = a.remove_front()`
: deletes and returns the item stored at the head of the list.

`a.del_front()`
: deletes the first element, without returning it.

`a.clear()`
: deletes all items from the list.

`a.ins_after(Pix i, item);`
: inserts item after position i. If i is null, insertion is at the front.

`a.del_after(Pix i);`
: deletes the element following i. If i is 0, the first item is deleted.

27.1 Doubly linked lists

Class `DLList` supports the following additional operations, as well as backward traversal via Pixes.

`x = a.remove_rear();`
: deletes and returns the item stored at the rear of the list.

`a.del_rear();`
: deletes the last element, without returning it.

`a.ins_before(Pix i, x)`
: inserts x before the i.

`a.del(Pix& iint dir = 1)`
: deletes the item at the current position, then advances forward if dir is positive, else backward.

28 Vector classes

The files '`g++-include/Vec.ccP`' and '`g++-include/AVec.ccP`' provide pseudo-generic standard array-based vector operations. The corresponding header files are '`g++-include/Vec.hP`' and '`g++-include/AVec.hP`'. Class `Vec` provides operations suitable for any base class that includes an equality operator. Subclass `AVec` provides additional arithmetic operations suitable for base classes that include the full complement of arithmetic operators.

`Vecs` are constructed and assigned by copying. Thus, they should normally be passed by reference in applications programs.

Several mapping functions are provided that allow programmers to specify operations on vectors as a whole.

For illustrative purposes assume that classes `intVec` and `intAVec` have been generated via `genclass`.

28.1 Constructors and assignment

`intVec a;` declares a to be an empty vector. Its size may be changed via resize.

`intVec a(10);`
declares a to be an uninitialized vector of ten elements (numbered 0-9).

`intVec b(6, 0);`
declares b to be a vector of six elements, all initialized to zero. Any value can be used as the initial fill argument.

`a = b;` Copies b to a. a is resized to be the same as b.

`a = b.at(2, 4)`
constructs a from the 4 elements of b starting at b[2].

Assume declarations of `intVec a, b, c` and `int i, x` in the following.

28.2 Status and access

`a.capacity();`
returns the number of elements that can be held in a.

`a.resize(20);`
sets a's length to 20. All elements are unchanged, except that if the new size is smaller than the original, than trailing elements are deleted, and if greater, trailing elements are uninitialized.

`a[i];` returns a reference to the i'th element of a, or produces an error if i is out of range.

`a.elem(i)`
returns a reference to the i'th element of a. Unlike the `[]` operator, i is not checked to ensure that it is within range.

`a == b;` returns true if a and b contain the same elements in the same order.

`a != b;` is the converse of a == b.

28.3 Constructive operations

`c = concat(a, b);`
: sets c to the new vector constructed from all of the elements of a followed by all of b.

`c = map(f, a);`
: sets c to the new vector constructed by applying int function f(int) to each element of a.

`c = merge(a, b, f);`
: sets c to the new vector constructed by merging the elements of ordered vectors a and b using ordering (comparison) function f.

`c = combine(f, a, b);`
: sets c to the new vector constructed by applying int function f(int, int) to successive pairs of a and b. The result has length the shorter of a and b.

`c = reverse(a)`
: sets c to a, with elements in reverse order.

28.4 Destructive operations

`a.reverse();`
: reverses a in-place.

`a.sort(f)`
: sorts a in-place using comparison function f. The sorting method is a variation of the quicksort functions supplied with GNU emacs.

`a.fill(0, 4, 2)`
: fills the 2 elements starting at a[4] with zero.

28.5 Other operations

`a.apply(f)`
: applies function f to each element in a.

`x = a.reduce(f, base)`
: accumulates the results of applying function f to successive elements of a starting with base.

`a.index(int targ);`
: returns the index of the leftmost occurrence of the target, or -1, if it does not occur.

`a.error(char* msg)`
: invokes the error handler. The default version prints the error message, then aborts.

28.6 AVec operations.

AVecs provide additional arithmetic operations. All vector-by-vector operators generate an error if the vectors are not the same length. The following operations are provided, for `AVecs a, b` and base element (scalar) `s`.

`a = b;` Copies b to a. a and b must be the same size.

`a = s;` fills all elements of a with the value s. a is not resized.

`a + s; a - s; a * s; a / s`
adds, subtracts, multiplies, or divides each element of a with the scalar.

`a += s; a -= s; a *= s; a /= s;`
adds, subtracts, multiplies, or divides the scalar into a.

`a + b; a - b; product(a, b), quotient(a, b)`
adds, subtracts, multiplies, or divides corresponding elements of a and b.

`a += b; a -= b; a.product(b); a.quotient(b);`
adds, subtracts, multiplies, or divides corresponding elements of b into a.

`s = a * b;` returns the inner (dot) product of a and b.

`x = a.sum();`
returns the sum of elements of a.

`x = a.sumsq();`
returns the sum of squared elements of a.

`x = a.min();`
returns the minimum element of a.

`x = a.max();`
returns the maximum element of a.

`i = a.min_index();`
returns the index of the minimum element of a.

`i = a.max_index();`
returns the index of the maximum element of a.

Note that it is possible to apply vector versions other arithmetic operators via the mapping functions. For example, to set vector b to the cosines of doubleVec a, use `b = map(cos, a);`. This is often more efficient than performing the operations in an element-by-element fashion.

29 Plex classes

A "Plex" is a kind of array with the following properties:

- Plexes may have arbitrary upper and lower index bounds. For example a Plex may be declared to run from indices -10 .. 10.
- Plexes may be dynamically expanded at both the lower and upper bounds of the array in steps of one element.
- Only elements that have been specifically initialized or added may be accessed.
- Elements may be accessed via indices. Indices are always checked for validity at run time. Plexes may be traversed via simple variations of standard array indexing loops.
- Plex elements may be accessed and traversed via Pixes.
- Plex-to-Plex assignment and related operations on entire Plexes are supported.
- Plex classes contain methods to help programmers check the validity of indexing and pointer operations.
- Plexes form "natural" base classes for many restricted-access data structures relying on logically contiguous indices, such as array-based stacks and queues.
- Plexes are implemented as pseudo-generic classes, and must be generated via the `genclass` utility.

Four subclasses of Plexes are supported: A `FPlex` is a Plex that may only grow or shrink within declared bounds; an `XPlex` may dynamically grow or shrink without bounds; an `RPlex` is the same as an `XPlex` but better supports indexing with poor locality of reference; a `MPlex` may grow or shrink, and additionally allows the logical deletion and restoration of elements. Because these classes are virtual subclasses of the "abstract" class `Plex`, it is possible to write user code such as `void f(Plex& a) ...` that operates on any kind of Plex. However, as with nearly any virtual class, specifying the particular Plex class being used results in more efficient code.

Plexes are implemented as a linked list of `IChunks`. Each chunk contains a part of the array. Chunk sizes may be specified within Plex constructors. Default versions also exist, that use a `#define'd` default. Plexes grow by filling unused space in existing chunks, if possible, else, except for FPlexes, by adding another chunk. Whenever Plexes grow by a new chunk, the default element constructors (i.e., those which take no arguments) for all chunk elements are called at once. When Plexes shrink, destructors for the elements are not called until an entire chunk is freed. For this reason, Plexes (like C++ arrays) should only be used for elements with default constructors and destructors that have no side effects.

Plexes may be indexed and used like arrays, although traversal syntax is slightly different. Even though Plexes maintain elements in lists of chunks, they are implemented so that iteration and other constructs that maintain locality of reference require very little overhead over that for simple array traversal Pix-based traversal is also supported. For example, for a plex, p, of ints, the following traversal methods could be used.

```
for (int i = p.low(); i < p.fence(); p.next(i)) use(p[i]);
for (int i = p.high(); i > p.ecnef(); p.prev(i)) use(p[i]);
for (Pix t = p.first(); t != 0; p.next(t)) use(p(i));
for (Pix t = p.last(); t != 0; p.prev(t)) use(p(i));
```

Except for MPlexes, simply using `++i` and `--i` works just as well as `p.next(i)` and `p.prev(i)` when traversing by index. Index-based traversal is generally a bit faster than Pix-based traversal.

`XPlexes` and `MPlexes` are less than optimal for applications in which widely scattered elements are indexed, as might occur when using Plexes as hash tables or "manually" allocated linked lists. In such applications, `RPlexes` are often preferable. `RPlexes` use a secondary chunk index table that requires slightly greater, but entirely uniform overhead per index operation.

Even though they may grow in either direction, Plexes are normally constructed so that their "natural" growth direction is upwards, in that default chunk construction leaves free space, if present, at the end of the plex. However, if the chunksize arguments to constructors are negative, they leave space at the beginning.

All versions of Plexes support the following basic capabilities. (letting `Plex` stand for the type name constructed via the genclass utility (e.g., `intPlex`, `doublePlex`)). Assume declarations of `Plex p, q`, `int i, j`, base element `x`, and Pix `pix`.

`Plex p;` Declares p to be an initially zero-sized Plex with low index of zero, and the default chunk size. For FPlexes, chunk sizes represent maximum sizes.

`Plex p(int size);`
Declares p to be an initially zero-sized Plex with low index of zero, and the indicated chunk size. If size is negative, then the Plex is created with free space at the beginning of the Plex, allowing more efficient add_low() operations. Otherwise, it leaves space at the end.

`Plex p(int low, int size);`
Declares p to be an initially zero-sized Plex with low index of low, and the indicated chunk size.

`Plex p(int low, int high, Base initval, int size = 0);`
Declares p to be a Plex with indices from low to high, initially filled with initval, and the indicated chunk size if specified, else the default or (high - low + 1), whichever is greater.

`Plex q(p);`
Declares q to be a copy of p.

`p = q;` Copies Plex q into p, deleting its previous contents.

`p.length()`
Returns the number of elements in the Plex.

`p.empty()`
Returns true if Plex p contains no elements.

`p.full()` Returns true if Plex p cannot be expanded. This always returns false for XPlexes and MPlexes.

`p[i]` Returns a reference to the i'th element of p. An exception (error) occurs if i is not a valid index.

`p.valid(i)`
: Returns true if i is a valid index into Plex p.

`p.low(); p.high();`
: Return the minimum (maximum) valid index of the Plex, or the high (low) fence if the plex is empty.

`p.ecnef(); p.fence();`
: Return the index one position past the minimum (maximum) valid index.

`p.next(i); i = p.prev(i);`
: Set i to the next (previous) index. This index may not be within bounds.

`p(pix)`
: returns a reference to the item at Pix pix.

`pix = p.first(); pix = p.last();`
: Return the minimum (maximum) valid Pix of the Plex, or 0 if the plex is empty.

`p.next(pix); p.prev(pix);`
: set pix to the next (previous) Pix, or 0 if there is none.

`p.owns(pix)`
: Returns true if the Plex contains the element associated with pix.

`p.Pix_to_index(pix)`
: If pix is a valid Pix to an element of the Plex, returns its corresponding index, else raises an exception.

`ptr = p.index_to_Pix(i)`
: if i is a valid index, returns a the corresponding Pix.

`p.low_element(); p.high_element();`
: Return a reference to the element at the minimum (maximum) valid index. An exception occurs if the Plex is empty.

`p.can_add_low(); p.can_add_high();`
: Returns true if the plex can be extended one element downward (upward). These always return true for XPlex and MPlex.

`j = p.add_low(x); j = p.add_high(x);`
: Extend the Plex by one element downward (upward). The new minimum (maximum) index is returned.

`j = p.del_low(); j = p.del_high()`
: Shrink the Plex by one element on the low (high) end. The new minimum (maximum) element is returned. An exception occurs if the Plex is empty.

`p.append(q);`
: Append all of Plex q to the high side of p.

`p.prepend(q);`
: Prepend all of q to the low side of p.

`p.clear()`
: Delete all elements, resetting p to a zero-sized Plex.

`p.reset_low(i);`
: Resets p to be indexed starting at low() = i. For example. if p were initially declared via `Plex p(0, 10, 0)`, and then re-indexed via `p.reset_low(5)`, it could then be indexed from indices 5 .. 14.

`p.fill(x)`
: sets all p[i] to x.

`p.fill(x, lo, hi)`
: sets all of p[i] from lo to hi, inclusive, to x.

`p.reverse()`
: reverses p in-place.

`p.chunk_size()`
: returns the chunk size used for the plex.

`p.error(const char * msg)`
: calls the resettable error handler.

MPlexes are plexes with bitmaps that allow items to be logically deleted and restored. They behave like other plexes, but also support the following additional and modified capabilities:

`p.del_index(i); p.del_Pix(pix)`
: logically deletes p[i] (p(pix)). After deletion, attempts to access p[i] generate a error. Indexing via low(), high(), prev(), and next() skip the element. Deleting an element never changes the logical bounds of the plex.

`p.undel_index(i); p.undel_Pix(pix)`
: logically undeletes p[i] (p(pix)).

`p.del_low(); p.del_high()`
: Delete the lowest (highest) undeleted element, resetting the logical bounds of the plex to the next lowest (highest) undeleted index. Thus, MPlex del_low() and del_high() may shrink the bounds of the plex by more than one index.

`p.adjust_bounds()`
: Resets the low and high bounds of the Plex to the indexes of the lowest and highest actual undeleted elements.

`int i = p.add(x)`
: Adds x in an unused index, if possible, else performs add_high.

`p.count()`
: returns the number of valid (undeleted) elements.

`p.available()`
: returns the number of available (deleted) indices.

`int i = p.unused_index()`
: returns the index of some deleted element, if one exists, else triggers an error. An unused element may be reused via undel.

`pix = p.unused_Pix()`
: returns the pix of some deleted element, if one exists, else 0. An unused element may be reused via undel.

30 Stacks

Stacks are declared as an "abstract" class. They are currently implemented in any of three ways.

`VStack` implement fixed sized stacks via arrays.

`XPStack` implement dynamically-sized stacks via XPlexes.

`SLStack` implement dynamically-size stacks via linked lists.

All possess the same capabilities. They differ only in constructors. VStack constructors require a fixed maximum capacity argument. XPStack constructors optionally take a chunk size argument. SLStack constructors take no argument.

Assume the declaration of a base element `x`.

`Stack s; or Stack s(int capacity)`
declares a Stack.

`s.empty()`
returns true if stack s is empty.

`s.full()` returns true if stack s is full. XPStacks and SLStacks never become full.

`s.length()`
returns the current number of elements in the stack.

`s.push(x)`
pushes x on stack s.

`x = s.pop()`
pops and returns the top of stack

`s.top()` returns a reference to the top of stack.

`s.del_top()`
pops, but does not return the top of stack. When large items are held on the stack it is often a good idea to use `top()` to inspect and use the top of stack, followed by a `del_top()`

`s.clear()`
removes all elements from the stack.

31 Queues

Queues are declared as an "abstract" class. They are currently implemented in any of three ways.

`VQueue` implement fixed sized Queues via arrays.

`XPQueue` implement dynamically-sized Queues via XPlexes.

`SLQueue` implement dynamically-size Queues via linked lists.

All possess the same capabilities; they differ only in constructors. `VQueue` constructors require a fixed maximum capacity argument. `XPQueue` constructors optionally take a chunk size argument. `SLQueue` constructors take no argument.

Assume the declaration of a base element `x`.

`Queue q; or Queue q(int capacity);`
declares a queue.

`q.empty()`
returns true if queue q is empty.

`q.full()` returns true if queue q is full. XPQueues and SLQueues are never full.

`q.length()`
returns the current number of elements in the queue.

`q.enq(x)` enqueues x on queue q.

`x = q.deq()`
dequeues and returns the front of queue

`q.front()`
returns a reference to the front of queue.

`q.del_front()`
dequeues, but does not return the front of queue

`q.clear()`
removes all elements from the queue.

32 Double ended Queues

Deques are declared as an "abstract" class. They are currently implemented in two ways.

`XPDeque` implement dynamically-sized Deques via XPlexes.

`DLDeque` implement dynamically-size Deques via linked lists.

All possess the same capabilities. They differ only in constructors. XPDeque constructors optionally take a chunk size argument. DLDeque constructors take no argument.

Double-ended queues support both stack-like and queue-like capabilities:

Assume the declaration of a base element `x`.

`Deque d; or Deque d(int initial_capacity)`
declares a deque.

`d.empty()`
returns true if deque d is empty.

`d.full()` returns true if deque d is full. Always returns false in current implementations.

`d.length()`
returns the current number of elements in the deque.

`d.enq(x)` inserts x at the rear of deque d.

`d.push(x)`
inserts x at the front of deque d.

`x = d.deq()`
dequeues and returns the front of deque

`d.front()`
returns a reference to the front of deque.

`d.rear()` returns a reference to the rear of the deque.

`d.del_front()`
deletes, but does not return the front of deque

`d.del_rear()`
deletes, but does not return the rear of the deque.

`d.clear()`
removes all elements from the deque.

33 Priority Queue class prototypes.

Priority queues maintain collections of objects arranged for fast access to the least element.

Several prototype implementations of priority queues are supported.

`XPPQs` implement 2-ary heaps via XPlexes.

`SplayPQs` implement PQs via Sleator and Tarjan's (JACM 1985) splay trees. The algorithms use a version of "simple top-down splaying" (described on page 669 of the article). The simple-splay mechanism for priority queue functions is loosely based on the one used by D. Jones in the C splay tree functions available from volume 14 of the uunet.uu.net archives.

`PHPQs` implement pairing heaps (as described by Fredman and Sedgewick in *Algorithmica*, Vol 1, p111-129). Storage for heap elements is managed via an internal freelist technique. The constructor allows an initial capacity estimate for freelist space. The storage is automatically expanded if necessary to hold new items. The deletion technique is a fast "lazy deletion" strategy that marks items as deleted, without reclaiming space until the items come to the top of the heap.

All PQ classes support the following operations, for some PQ class `Heap`, instance `h`, `Pix ind`, and base class variable `x`.

`h.empty()`
: returns true if there are no elements in the PQ.

`h.length()`
: returns the number of elements in h.

`ind = h.enq(x)`
: Places x in the PQ, and returns its index.

`x = h.deq()`
: Dequeues the minimum element of the PQ into x, or generates an error if the PQ is empty.

`h.front()`
: returns a reference to the minimum element.

`h.del_front()`
: deletes the minimum element.

`h.clear();`
: deletes all elements from h;

`h.contains(x)`
: returns true if x is in h.

`h(ind)` returns a reference to the item indexed by ind.

`ind = h.first()`
: returns the Pix of first item in the PQ or 0 if empty. This need not be the Pix of the least element.

`h.next(ind)`
: advances ind to the Pix of next element, or 0 if there are no more.

`ind = h.seek(x)`
: Sets ind to the Pix of x, or 0 if x is not in h.

`h.del(ind)`
: deletes the item with Pix ind.

34 Set class prototypes

Set classes maintain unbounded collections of items containing no duplicate elements.

These are currently implemented in several ways, differing in representation strategy, algorithmic efficiency, and appropriateness for various tasks. (Listed next to each are average (followed by worst-case, if different) time complexities for [a] adding, [f] finding (via seek, contains), [d] deleting, elements, and [c] comparing (via ==, <=) and [m] merging (via |=, -=, &=) sets).

`XPSets` implement unordered sets via XPlexes. ([a O(n)], [f O(n)], [d O(n)], [c O(n^2)] [m O(n^2)]).

`OXPSets` implement ordered sets via XPlexes. ([a O(n)], [f O(log n)], [d O(n)], [c O(n)] [m O(n)]).

`SLSets` implement unordered sets via linked lists ([a O(n)], [f O(n)], [d O(n)], [c O(n^2)] [m O(n^2)]).

`OSLSets` implement ordered sets via linked lists ([a O(n)], [f O(n)], [d O(n)], [c O(n)] [m O(n)]).

`AVLSets` implement ordered sets via threaded AVL trees ([a O(log n)], [f O(log n)], [d O(log n)], [c O(n)] [m O(n)]).

`BSTSets` implement ordered sets via binary search trees. The trees may be manually rebalanced via the O(n) `balance()` member function. ([a O(log n)/O(n)], [f O(log n)/O(n)], [d O(log n)/O(n)], [c O(n)] [m O(n)]).

`SplaySets`
implement ordered sets via Sleator and Tarjan's (JACM 1985) splay trees. The algorithms use a version of "simple top-down splaying" (described on page 669 of the article). (Amortized: [a O(log n)], [f O(log n)], [d O(log n)], [c O(n)] [m O(n log n)]).

`VHSets` implement unordered sets via hash tables. The tables are automatically resized when their capacity is exhausted. ([a O(1)/O(n)], [f O(1)/O(n)], [d O(1)/O(n)], [c O(n)/O(n^2)] [m O(n)/O(n^2)]).

`VOHSets` implement unordered sets via ordered hash tables The tables are automatically resized when their capacity is exhausted. ([a O(1)/O(n)], [f O(1)/O(n)], [d O(1)/O(n)], [c O(n)/O(n^2)] [m O(n)/O(n^2)]).

`CHSets` implement unordered sets via chained hash tables. ([a O(1)/O(n)], [f O(1)/O(n)], [d O(1)/O(n)], [c O(n)/O(n^2)] [m O(n)/O(n^2)]).

The different implementations differ in whether their constructors require an argument specifying their initial capacity. Initial capacities are required for plex and hash table based Sets. If none is given `DEFAULT_INITIAL_CAPACITY` (from '`<T>defs.h`') is used.

Sets support the following operations, for some class `Set`, instances `a` and `b`, `Pix ind`, and base element `x`. Since all implementations are virtual derived classes of the `<T>Set` class, it is possible to mix and match operations across different implementations, although, as

usual, operations are generally faster when the particular classes are specified in functions operating on Sets.

Pix-based operations are more fully described in the section on Pixes. See Chapter 9 [Pix], page 33

`Set a; or Set a(int initial_size);`
: Declares a to be an empty Set. The second version is allowed in set classes that require initial capacity or sizing specifications.

`a.empty()`
: returns true if a is empty.

`a.length()`
: returns the number of elements in a.

`Pix ind = a.add(x)`
: inserts x into a, returning its index.

`a.del(x)` deletes x from a.

`a.clear()`
: deletes all elements from a;

`a.contains(x)`
: returns true if x is in a.

`a(ind)` returns a reference to the item indexed by ind.

`ind = a.first()`
: returns the Pix of first item in the set or 0 if the Set is empty. For ordered Sets, this is the Pix of the least element.

`a.next(ind)`
: advances ind to the Pix of next element, or 0 if there are no more.

`ind = a.seek(x)`
: Sets ind to the Pix of x, or 0 if x is not in a.

`a == b` returns true if a and b contain all the same elements.

`a != b` returns true if a and b do not contain all the same elements.

`a <= b` returns true if a is a subset of b.

`a |= b` Adds all elements of b to a.

`a -= b` Deletes all elements of b from a.

`a &= b` Deletes all elements of a not occurring in b.

35 Bag class prototypes

Bag classes maintain unbounded collections of items potentially containing duplicate elements.

These are currently implemented in several ways, differing in representation strategy, algorithmic efficiency, and appropriateness for various tasks. (Listed next to each are average (followed by worst-case, if different) time complexities for [a] adding, [f] finding (via seek, contains), [d] deleting elements).

`XPBags` implement unordered Bags via XPlexes. ([a O(1)], [f O(n)], [d O(n)]).

`OXPBags` implement ordered Bags via XPlexes. ([a O(n)], [f O(log n)], [d O(n)]).

`SLBags` implement unordered Bags via linked lists ([a O(1)], [f O(n)], [d O(n)]).

`OSLBags` implement ordered Bags via linked lists ([a O(n)], [f O(n)], [d O(n)]).

`SplayBags`
implement ordered Bags via Sleator and Tarjan's (JACM 1985) splay trees. The algorithms use a version of "simple top-down splaying" (described on page 669 of the article). (Amortized: [a O(log n)], [f O(log n)], [d O(log n)]).

`VHBags` implement unordered Bags via hash tables. The tables are automatically resized when their capacity is exhausted. ([a O(1)/O(n)], [f O(1)/O(n)], [d O(1)/O(n)]).

`CHBags` implement unordered Bags via chained hash tables. ([a O(1)/O(n)], [f O(1)/O(n)], [d O(1)/O(n)]).

The implementations differ in whether their constructors require an argument to specify their initial capacity. Initial capacities are required for plex and hash table based Bags. If none is given `DEFAULT_INITIAL_CAPACITY` (from '`<T>defs.h`') is used.

Bags support the following operations, for some class `Bag`, instances `a` and `b`, `Pix ind`, and base element `x`. Since all implementations are virtual derived classes of the `<T>Bag` class, it is possible to mix and match operations across different implementations, although, as usual, operations are generally faster when the particular classes are specified in functions operating on Bags.

Pix-based operations are more fully described in the section on Pixes. See Chapter 9 [Pix], page 33

`Bag a; or Bag a(int initial_size)`
Declares a to be an empty Bag. The second version is allowed in Bag classes that require initial capacity or sizing specifications.

`a.empty()`
returns true if a is empty.

`a.length()`
returns the number of elements in a.

`ind = a.add(x)`
inserts x into a, returning its index.

`a.del(x)` deletes one occurrence of x from a.

`a.remove(x)`
deletes all occurrences of x from a.

`a.clear()`
deletes all elements from a;

`a.contains(x)`
returns true if x is in a.

`a.nof(x)` returns the number of occurrences of x in a.

`a(ind)` returns a reference to the item indexed by ind.

`int = a.first()`
returns the Pix of first item in the Bag or 0 if the Bag is empty. For ordered Bags, this is the Pix of the least element.

`a.next(ind)`
advances ind to the Pix of next element, or 0 if there are no more.

`ind = a.seek(x, Pix from = 0)`
Sets ind to the Pix of the next occurrence x, or 0 if there are none. If from is 0, the first occurrence is returned, else the following from.

36 Map Class Prototypes

Maps support associative array operations (insertion, deletion, and membership of records based on an associated key). They require the specification of two types, the key type and the contents type.

These are currently implemented in several ways, differing in representation strategy, algorithmic efficiency, and appropriateness for various tasks. (Listed next to each are average (followed by worst-case, if different) time complexities for [a] accessing (via op [], contains), [d] deleting elements).

`AVLMaps` implement ordered Maps via threaded AVL trees ([a O(log n)], [d O(log n)]).

`RAVLMaps` Similar, but also maintain ranking information, used via `ranktoPix(int r)`, that returns the `Pix` of the item at rank r, and `rank(key)` that returns the rank of the corresponding item. ([a O(log n)], [d O(log n)]).

`SplayMaps`
implement ordered Maps via Sleator and Tarjan's (JACM 1985) splay trees. The algorithms use a version of "simple top-down splaying" (described on page 669 of the article). (Amortized: [a O(log n)], [d O(log n)]).

`VHMaps` implement unordered Maps via hash tables. The tables are automatically resized when their capacity is exhausted. ([a O(1)/O(n)], [d O(1)/O(n)]).

`CHMaps` implement unordered Maps via chained hash tables. ([a O(1)/O(n)], [d O(1)/O(n)]).

The different implementations differ in whether their constructors require an argument specifying their initial capacity. Initial capacities are required for hash table based Maps. If none is given `DEFAULT_INITIAL_CAPACITY` (from '`<T>defs.h`') is used.

All Map classes share the following operations (for some Map class, `Map` instance `d`, `Pix ind` and key variable `k`, and contents variable `x`).

Pix-based operations are more fully described in the section on Pixes. See Chapter 9 [Pix], page 33

`Map d(x); Map d(x, int initial_capacity)`
Declare d to be an empty Map. The required argument, x, specifies the default contents, i.e., the contents of an otherwise uninitialized location. The second version, specifying initial capacity is allowed for Maps with an initial capacity argument.

`d.empty()`
returns true if d contains no items.

`d.length()`
returns the number of items in d.

`d[k]` returns a reference to the contents of item with key k. If no such item exists, it is installed with the default contents. Thus d[k] = x installs x, and x = d[k] retrieves it.

`d.contains(k)`
: returns true if an item with key field k exists in d.

`d.del(k)` deletes the item with key k.

`d.clear()`
: deletes all items from the table.

`x = d.dflt()`
: returns the default contents.

`k = d.key(ind)`
: returns a reference to the key at Pix ind.

`x = d.contents(ind)`
: returns a reference to the contents at Pix ind.

`ind = d.first()`
: returns the Pix of the first element in d, or 0 if d is empty.

`d.next(ind)`
: advances ind to the next element, or 0 if there are no more.

`ind = d.seek(k)`
: returns the Pix of element with key k, or 0 if k is not in d.

37 C++ version of the GNU getopt function

The GetOpt class provides an efficient and structured mechanism for processing command-line options from an application program. The sample program fragment below illustrates a typical use of the GetOpt class for some hypothetical application program:

```
#include <stdio.h>
#include <GetOpt.h>
//...
int debug_flag, compile_flag, size_in_bytes;

int
main (int argc, char **argv)
{
  // Invokes ctor `GetOpt (int argc, char **argv,
  //                       char *optstring);'
  GetOpt getopt (argc, argv, "dcs:");
  int option_char;

  // Invokes member function `int operator ()(void);'
  while ((option_char = getopt ()) != EOF)
    switch (option_char)
      {
         case 'd': debug_flag = 1; break;
         case 'c': compile_flag = 1; break;
         case 's': size_in_bytes = atoi (getopt.optarg); break;
         case '?': fprintf (stderr,
                            "usage: %s [dcs<size>]\n", argv[0]);
      }
}
```

Unlike the C library version, the libg++ GetOpt class uses its constructor to initialize class data members containing the argument count, argument vector, and the option string. This simplifies the interface for each subsequent call to member function `int operator ()(void)`.

The C version, on the other hand, uses hidden static variables to retain the option string and argument list values between calls to `getopt`. This complicates the `getopt` interface since the argument count, argument vector, and option string must be passed as parameters for each invocation. For the C version, the loop in the previous example becomes:

```
while ((option_char = getopt (argc, argv, "dcs:")) != EOF)
  // ...
```

which requires extra overhead to pass the parameters for every call.

Along with the GetOpt constructor and `int operator ()(void)`, the other relevant elements of class GetOpt are:

`char *optarg`
: Used for communication from `operator ()(void)` to the caller. When `operator ()(void)` finds an option that takes an argument, the argument value is stored here.

`int optind`

Index in `argv` of the next element to be scanned. This is used for communication to and from the caller and for communication between successive calls to `operator ()(void)`.

When `operator ()(void)` returns EOF, this is the index of the first of the non-option elements that the caller should itself scan.

Otherwise, `optind` communicates from one call to the next how much of `argv` has been scanned so far.

The libg++ version of GetOpt acts like standard UNIX `getopt` for the calling routine, but it behaves differently for the user, since it allows the user to intersperse the options with the other arguments.

As GetOpt works, it permutes the elements of `argv` so that, when it is done, all the options precede everything else. Thus all application programs are extended to handle flexible argument order.

Setting the environment variable _POSIX_OPTION_ORDER disables permutation. Then the behavior is completely standard.

38 Projects and other things left to do

38.1 Coming Attractions

Some things that will probably be available in libg++ in the near future:

- Revamped C-compatibility header files that will be compatible with the forthcoming (ANSI-based) GNU libc.a
- A revision of the File-based classes that will use the GNU stdio library, and also be 100% compatible (even at the streambuf level) with the AT&T 2.0 stream classes.
- Additional container class prototypes.
- generic Matrix class prototypes.
- A task package probably based on Dirk Grunwald's threads package.

38.2 Wish List

Some things that people have mentioned that they would like to see in libg++, but for which there have not been any offers:

- A method to automatically convert or incorporate libg++ classes so they can be used directly in Gorlen's OOPS environment.
- A class browser.
- A better general exception-handling strategy.
- Better documentation.

38.3 How to contribute

Programmers who have written C++ classes that they believe to be of general interest are encourage to write to dl at rocky.oswego.edu. Contributing code is not difficult. Here are some general guidelines:

- FSF must maintain the right to accept or reject potential contributions. Generally, the only reasons for rejecting contributions are cases where they duplicate existing or nearly-released code, contain unremovable specific machine dependencies, or are somehow incompatible with the rest of the library.
- Acceptance of contributions means that the code is accepted for adaptation into libg++. FSF must reserve the right to make various editorial changes in code. Very often, this merely entails formatting, maintenance of various conventions, etc. Contributors are always given authorship credit and shown the final version for approval.
- Contributors must assign their copyright to FSF via a form sent out upon acceptance. Assigning copyright to FSF ensures that the code may be freely distributed.
- Assistance in providing documentation, test files, and debugging support is strongly encouraged.

Extensions, comments, and suggested modifications of existing libg++ features are also very welcome.

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