Lecture 15: C++

Program structure issues

- how to cope with ever bigger programs?
- objects
  - user-defined data types
- components
  - related objects
- frameworks
  - automatic generation of routine code
- interfaces
  - boundaries between code that provides a service and code that uses it
- information hiding
  - what parts of an implementation are visible
- resource management
  - creation and initialization of entities
  - maintaining state
  - ownership: sharing and copying
  - memory management
  - cleanup
- error handling; exceptions

C++

- **designed & implemented by Bjarne Stroustrup**
  - started ~ 1980; ISO C++98 standard; C++11; C++14; C++17; C++ 20 on track
- **a better C**
  - almost completely upwards compatible with C
  - more checking of interfaces (e.g., function prototypes, added to ANSI C)
  - other features for easier programming
- **data abstraction**
  - methods reveal only WHAT is done
  - classes hide HOW something is done in a program, can be changed as program evolves
- **object-oriented programming**
  - *inheritance* -- define new types that inherit properties from previous types
  - *polymorphism* or dynamic binding -- function to be called is determined by data type of specific object at run time
- **templates or "generic" programming**
  - compile-time parameterized types
  - define families of related types, where the type is a parameter
- **a "multi-paradigm" language**
  - lots of ways to write code

C++ synopsis

- **data abstraction with classes**
  - a class defines a type that can be used to declare variables of that type, control access to representation
- **operator and function name overloading**
  - almost all C operators (including =, +=..., **( )**, **[ ]**, **->**, argument passing and function return) can be overloaded to apply to user-defined types
- **control of creation and destruction of objects**
  - initialization of class objects, recovery of resources on destruction
- **inheritance: derived classes built on base classes**
  - virtual functions override base functions
  - multiple inheritance: inherit from more than one class
- **exception handling**
- **namespaces for separate libraries**
- **templates (generic types)**
  - Standard Template Library: generic algorithms on generic containers
  - template metaprogramming: execution of C++ code *during compilation*
- **(almost) upward compatible with C except for new keywords**

A simple stack class

```
// stk3.c: new, destructors, delete

class stack {
  private:
        int *stk;     // allocated dynamically
        int *sp;      // next free place
  public:
        int push(int);
        int pop();
        stack();      // constructor
        stack(int n); // constructor
        ~stack();     // destructor
};

stack::stack() {
        stk = new int[100];  sp = stk;
}
stack::stack(int n) {
        stk = new int[n];  sp = stk;
}
stack::~stack() {
        delete [] stk;
}
```

Constructors and destructors

- **constructor: create a new object** (including initialization)
  - implicitly, by entering the scope where it is declared
  - explicitly, by calling **`new`**
- **destructor: destroy an existing object** (including cleanup)
  - implicitly, by leaving the scope where it is declared
  - explicitly, by calling **`delete`** on an object created by **`new`**
- **construction includes initialization, so it may be parameterized**
  - by multiple constructor functions with different args
  - an example of function overloading
- **`new` can be used to create an array of objects**
  - in which case **`delete`** can delete the entire array

Implicit and explicit allocation and deallocation

- implicit:

```
f() {
    int i;
    stack s;      // calls constructor stack::stack()
    ...
    // calls s.~stack() implicitly
}
```

- explicit:

```
f() {
    int *ip = new int;
    stack *sp = new stack;    // calls stack::stack()
    ...
    delete sp; // calls sp->~stack()
    delete ip;
    ...
}
```

Operator overloading

- **almost all C operators can be overloaded**
  - a new meaning can be defined when one operand of an operator is a user-defined (class) type
  - define **operator +** for object of type **T**

    `T T::operator+(int n) {...}`

    `T T::operator+(double d) {...}`
  - define regular **+** for object(s) of type **T**

    `T operator +(T f, int n) {...}`
  - can't redefine operators for built-in types

    `int operator +(int, int)` is ILLEGAL
  - can't define new operators
  - can't change precedence and associativity

    e.g., ^ is low precedence even if used for exponentiation
- **3 short examples**
  - complex numbers: overloading arithmetic operators
  - IO streams: overloading << and >> for input and output
  - subscripting: overloading [ ]
- **later: overloading assignment and function calls**

Operator overloading: a complex number class

```
class complex {
    double re, im;
  public:
    complex(double r = 0, double i = 0)
        { re = r; im = i; }  // constructor

    friend complex operator +(complex,complex);
    friend complex operator *(complex,complex);
};

complex operator +(complex c1, complex c2) {
    return complex(c1.re+c2.re, c1.im+c2.im);
}
```

- complex declarations and expressions

```
complex a(1.1, 2.2), b(3.3), c(4), d;

d = 2 * a;
```

2 coerced to 2.0 (C promotion rule)

then constructor invoked to make complex(2.0, 0.0)

- operator overloading works well for arithmetic types

References: controlled pointers

- need a way to access object, not a copy of it
- in C, use pointers

```
void swap(int *x, int *y) {
   int temp;
   temp = *x; *x = *y; *y = temp;
}
swap(&a, &b);
```

- in C++, references attach a name to an object
- a way to get "call by reference" (var) parameters without using explicit pointers

```
void swap(int &x, int &y) {
   int temp;
   temp = x; x = y; y = temp;
}
swap(a, b);   // pointers are implicit
```

- because it's really a pointer, a reference provides a way to access an object without copying it

A vector class: overloading [ ]

```
class ivec {  // vector of ints
   int *v;          // pointer to an array
   int size;        // number of elements
  public:
   ivec(int n) { v = new int[size = n]; }

   int& operator[](int n) {  // checked
      assert(n >= 0 && n < size);
      return v[n];
   }
};

   ivec iv(10);    // declaration
   iv[10] = 1;     // checked access on left side of =
```

- operator[ ] returns a reference
- a reference gives access to the object so it can be changed
- necessary so we can use [ ] on left side of assignment

Input and output with iostreams

- overload operator << for output and >> for input
  - very low precedence, left-associative, so

```
cout << e1 << e2 << e3
```

  - is parsed as

```
(((cout << e1) << e2) << e3)
```

```
#include <iostream>
  ostream& operator<<(ostream& os, const complex& c) {
     os << "(" << c.real() << ", " << c.imag() << ")";
     return os;
  }
  while (cin >> name >> val) {
       cout << name << " = "
            << val << "\n";
   }
```

- takes a reference to iostream and data item
- returns the reference so can use same iostream for next expression
- each item is converted into the proper type
- iostreams cin, cout, cerr already open (== stdin, stdout, stderr)

Formatter in C++

```
#include <iostream>
#include <string>
using namespace std;

const int maxlen = 60;
string line;
void addword(const string&);
void println();

main(int argc, char **argv) {
   string word;
   while (cin >> word)
      addword(word);
   println();
}
void addword(const string& w) {
   if (line.length() + w.length() > maxlen)
      println();
   if (line.length() > 0)
      line += " ";
   line += w;
}
void println() {
   if (line.length() > 0) {
      cout << line << endl;
      line = "";
   }
}
```

Summary of references

- a reference is in effect a very constrained pointer
  - points to a specific object
  - can't be changed, though whatever it points to can certainly be changed
- provides control of pointer operations for applications where addresses must be passed for access to an object
  - e.g., a function that will change something in the caller
  - like swap(x, y)
- provides notational convenience
  - compiler takes care of all * and & properly
- permits some non-intuitive operations like the overloading of `[]`
  - `int &operator[]` permits use of `[]` on left side of assignment
  - `v[e]` means `v.operator[](e)`

Life cycle of an object

- **construction: creating a new object**
  - implicitly, by entering the scope where it is declared
  - explicitly, by calling **`new`**
  - construction includes initialization
- **copying: using existing object to make a new one**
  - "copy constructor" makes a new object from existing one of the same kind
  - implicitly invoked in (some) declarations, function arguments, function return
- **assignment: changing an existing object**
  - occurs explicitly with `=, +=,` etc.
  - meaning of explicit and implicit copying must be part of the representation
    default is member-wise assignment and initialization
- **destruction: destroying an existing object**
  - implicitly, by leaving the scope where it is declared
  - explicitly, by calling **`delete`** on an object created by **`new`**
  - includes cleanup and resource recovery

Strings: constructors & assignment

- **another type that C and C++ don't provide**
- **implementation of a String class combines**
  - constructors, destructors, copy constructor
  - assignment, operator =
  - constant references
  - handles, reference counts, garbage collection

- **Strings should behave like strings in Awk, Python, Java, …**
  - can assign to a string, copy a string, etc.
  - can pass them to functions, return as results, …
- **storage managed automatically**
  - no explicit allocation or deletion
  - grow and shrink automatically
  - efficient

- **can create String from "..." C char* string**
- **can pass String to functions expecting char***

"Copy constructor"

- when a class object is passed to a function, returned from a function, or used as an initializer in a declaration, a copy is made:

```
String substr(String s, int start, int len)
```

- a "copy constructor" creates an object of class X from an existing object of class X
- obvious way to write it causes an infinite loop:

```
class String {
    String(String s) {...} // doesn't work
};
```

- copy constructor parameter must be a reference so object can be accessed without copying

```
class String {
    String(const String& s) {...}
    // ...
};
```

- copy constructor is necessary for declarations, function arguments, function return values

String class

```
class String {
  private:
    char    *sp;
  public:
    String() { sp=strdup(""); }  // String s;
    String(const char *t) { sp=strdup(t); } // String s("abc");
    String(const String &t) { sp=strdup(t.sp); } // String s(t);
    ~String() { delete [] sp; }

    String& operator =(const char *);// s="abc"
    String& operator =(const String &);// s1=s2

    const char *s() { return sp; } // as char*
};
```

- assignment is not the same as initialization
  - changes the state of an existing object
- the meaning of assignment is defined by a member function named **`operator=`**

  `x = y` means **`x.operator=(y)`**

Assignment operators

```
String& String::operator =(const char *t) { // s = "abc"
    delete [] sp;
    sp = strdup(t);
    return *this;
}
String& String::operator=(const String& t) { // s1 = s2
    if (this != &t) {  // avoid s1 = s1
        delete [] sp;
        sp = strdup(t.sp);
    }
    return *this;
}
```

- in a member function, `this` points to current object, so `*this` is the object (returned as a reference)
- assignment operators almost always end with

```
        return *this
```

which returns a reference to the LHS

– permits multiple assignment `s1 = s2 = s3`

Handles and reference counts

- how to avoid unnecessary copying for classes like strings, arrays, other containers

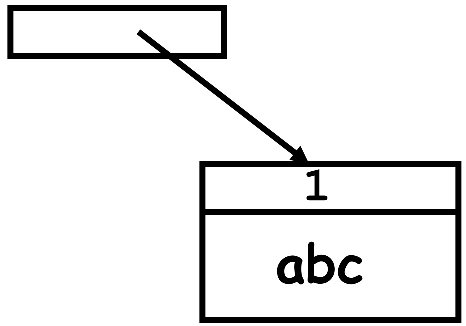
- copy constructor may allocate new memory even if unnecessary
  - e.g., in **`f(const String& s)`** string value would be copied even if it won't be changed by **`f`**

- a handle class manages a pointer to the real data
- implementation class manages the real data
  - string data itself
  - counter of how many Strings refer to that data
  - when String is copied, increment the ref count
  - when String is destroyed, decrement the ref count
  - when last reference is gone, free all allocated memory

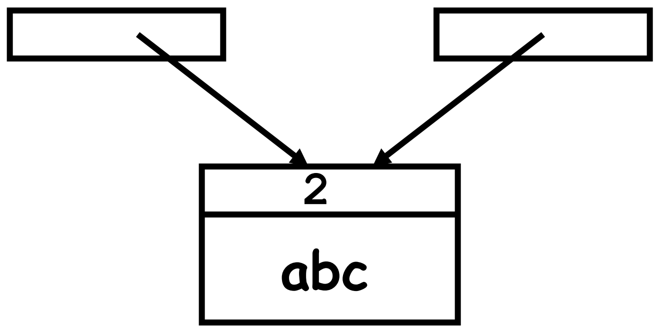
- with a handle class, copying only increments reference count
  - "shallow" copy instead of "deep" copy

Reference counts

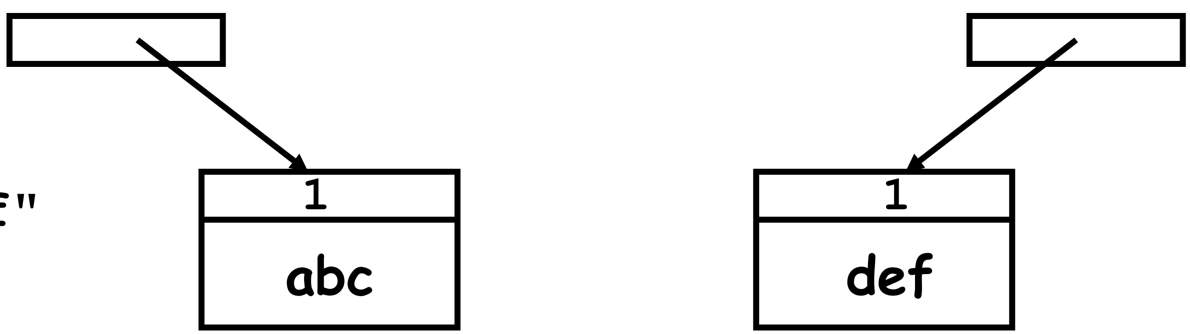
`s = "abc"`



`t = s`



`t = "def"`



Inheritance

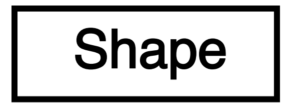
- **a way to create or describe one class in terms of another**
  - "a D is like a B, with these extra properties..."
  - "a D is a B, plus…"
  - B is the **base** class or **super**class
  - D is the **derived** class or **sub**class

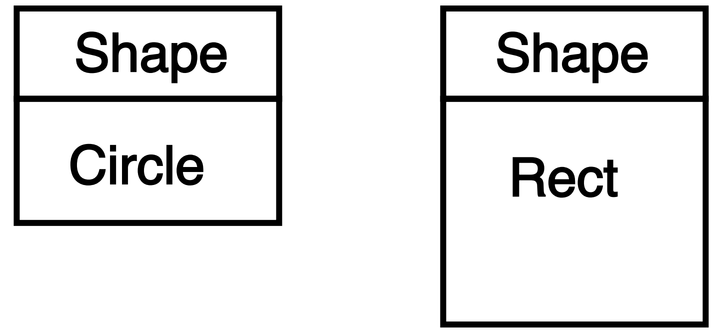
    C++, Perl, Python, … use base/derived; Java, Ruby, … use super/sub

- **inheritance is used for classes that model strongly related concepts**
  - objects share some common properties, behaviors, ...
  - and have some properties and behaviors that are different

- **base class contains aspects common to all**
- **derived classes contain aspects different for different kinds**

Derived classes






```cpp
class Shape {
     int color;
     virtual Shape& draw();
     // other items common to all Shapes
};
class Rect: public Shape {
    Point origin; double ht, wid;
    Shape& draw() {...} // how to draw a rectangle
};
class Circle: public Shape {
    Point center; double rad;
    Shape& draw() {...} // how to draw a circle
};
```

- a Rect is a derived class of (a kind of) Shape
  - a Rect "is a" Shape
  - inherits all members of Shape
  - adds its own members
- a Circle is also a derived class of Shape
  - adds its own different members

Virtual Functions

- a function in a base class that can be overridden by a function in a derived class (with same name and arguments)

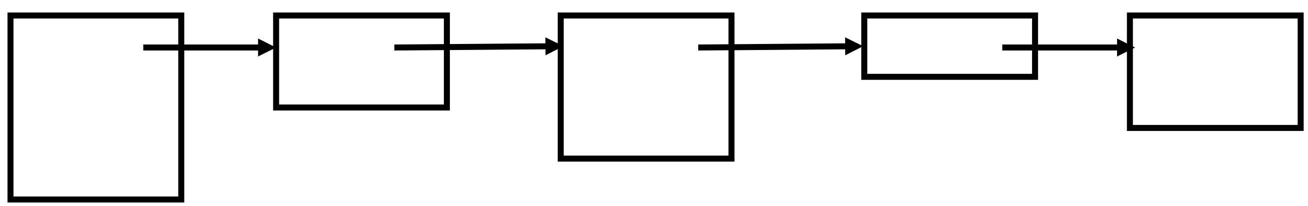
```
class Shape {
    public:
        virtual Shape& draw();
        ...
};
```

- "virtual" means that a derived class may provide its own version of this function, which will be called automatically for instances of that derived class
- the base class can provide a default implementation
- if the base class is "pure", it must be derived from
  - pure base class can't exist on its own; no default implementation

Polymorphism

- when a pointer or reference to a base-class type points to a derived-class object
- and you use that pointer or reference to call a virtual function
- this calls the derived-class function
- "polymorphism": proper function to call is determined at run-time
- e.g., drawing Shapes on a linked list:

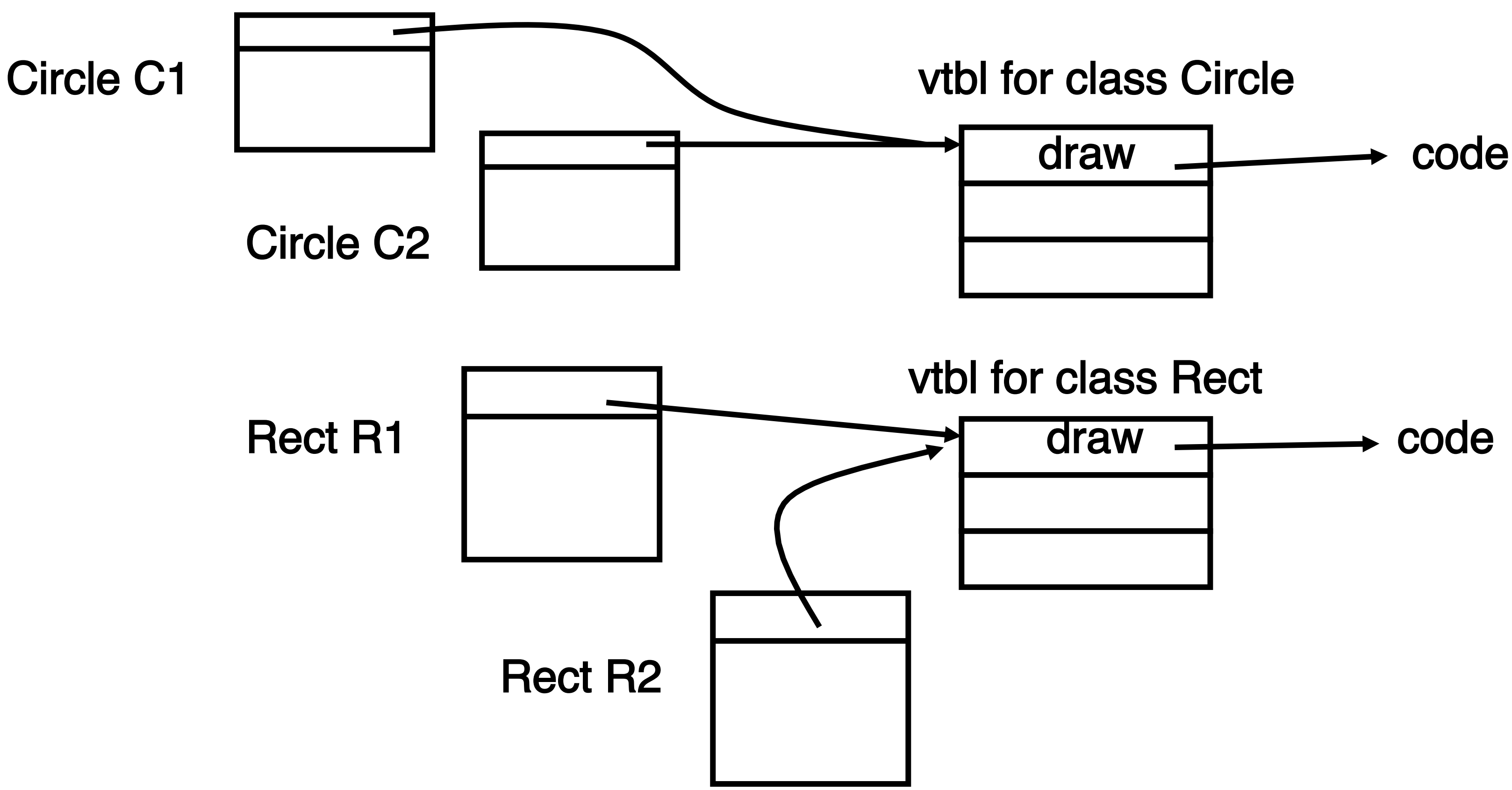
```
draw_all(Shape *sp) {
    for ( ; sp != NULL; sp = sp->next)
        sp->draw();
}
```



- the virtual function mechanism automatically calls the right draw() function for each object
- the loop does not change if more kinds of Shapes are added

Implementation of virtual functions

- each class object that has virtual functions has one extra word that holds a pointer to a table of virtual function pointers ("vtbl")
- each class with virtual functions has one vtbl
- a call to a virtual function calls it indirectly through the vtbl



Summary of inheritance

- a way to describe a family of types
- by collecting similarities (base class)
- and separating differences (derived classes)

- polymorphism: proper member functions determined at run time
  – virtual functions are the C++ mechanism

- not every class needs inheritance
  – may complicate without compensating benefit

- use composition instead of inheritance?
  – an object contains (has) an object
    rather than inheriting from it
- "is-a" versus "has-a"
  – inheritance describes "is-a" relationships
  – composition describes "has-a" relationships

Templates (parameterized types, generics)

- another approach to polymorphism
- compile time, not run time
- a template specifies a class or a function that is *the same* for several types
  - except for one or more **type parameters**

- e.g., a vector template defines a class of vectors that can be instantiated for any particular type

```
vector<int>
vector<String>
vector<vector<int>>
```

- templates versus inheritance:
  - use inheritance when behaviors are different for different types
    drawing different Shapes is different
  - use template when behaviors are the same, regardless of types
    accessing the n-th element of a vector is the same,
    no matter what type the vector is

Vector template class

- vector class defined as a template, to be instantiated with different types of elements

```
template <typename T> class vector {
    T *v;      // pointer to array
    int size; // number of elements
  public:
    vector(int n=1) { v = new T[size = n]; }
    T& operator [](int n) {
        assert(n >= 0 && n < size);
        return v[n];
    }
};

vector<int> iv(100);          // vector of ints
vector<complex> cv(20);       // vector of complex
vector<vector<int>> vvi(10); // vector of vector of int
vector<double> d;             // default size
```

- compiler instantiates whatever types are used

Standard Template Library (STL)

Alex Stepanov

(GE > Bell Labs > HP > SGI > Compaq > Adobe > A9 > ...)

- general-purpose library of
  containers (vector, list, set, map, …)
  generic algorithms (find, replace, sort, …)
- algorithms written in terms of iterators performing specified access patterns on containers
  - rules for how iterators work, how containers have to support them
- generic: every algorithm works on a variety of containers, including built-in types
  - e.g., find elements in char array, vector<int>, list<…>
- iterators: generalization of pointer for uniform access to items in a container

Containers and algorithms

- **STL container classes contain objects of any type**
  - sequences: vector, list, slist, deque
  - sorted set, map, multiset, multimap; unordered_set, unordered_map
- **each container class is a template that can be instantiated to contain any type of object**
- **generic algorithms**
  - find, find_if, find_first_of, search, ...
  - count, min, max, …
  - copy, replace, fill, remove, reverse, …
  - accumulate, inner_product, partial_sum, …
  - sort
  - binary_search, merge, set_union, …
- **performance guarantees**
  - each combination of algorithm and iterator type specifies worst-case (O(…)) performance bound

    e.g., maps are O(log n) access, vectors are O(1) access

Iterators

- a generalization of C pointers

  ```
  for (p = begin; p < end; ++p)
      do something with *p
  ```

- range from `begin()` to just before `end()`   [begin, end)
- `++iter` advances to the next if there is one
- `*iter` dereferences (points to value)
- uses operator `!=` to test for end of range

  ```
  for (iter i = v.begin(); i != v.end(); ++i)
      do something with *i
  ```

```
#include <vector>
#include <iterator>
using namespace ::std;
int main() {
   vector<double> v;
   for (int i = 1; i <= 10; i++)
      v.push_back(i);
   vector<double>::const_iterator it;
   double sum = 0;
   for (it = v.begin(); it != v.end(); ++it)
      sum += *it;
   printf("%g\n", sum);
}
```

Iterators (2)

- no change to loop if type or representation changes

- not all containers support all iterator operations

- input iterator
  - can only read items in order, can't store into them (e.g., input from file)
- output iterator
  - can only write items in order, can't read them (output to a file)
- forward iterator
  - can read/write items in order, can't go backwards (singly-linked list)
- bidirectional iterator
  - can read/write items in either order (doubly-linked list)
- random access iterator
  - can access items in any order (array)

Example: STL sort

```
#include <iostream>
#include <iterator>
#include <vector>
#include <string>
#include <algorithm>
using namespace ::std;

int main() {  // sort stdin by lines
    vector<string> vs;
    string tmp;
    while (getline(cin, tmp))
        vs.push_back(tmp);
    sort(vs.begin(), vs.end());
    copy(vs.begin(), vs.end(),
        ostream_iterator<string>(cout, "\n"));
}
```

- vs.push_back(s) pushes s onto "back" (end) of vs
- 3rd argument of copy is a "function object" that calls a function for each iteration
  - uses overloaded operator()

Word frequency count: C++ STL

```
#include <iostream>
#include <map>
#include <string>

int main() {
    string temp;
    map<string, int> v;
    map<string, int>::const_iterator i;

    while (cin >> temp)
        v[temp]++;
    for (auto i : v)
        cout << i.first << " " << i.second << "\n";
}
```

Word frequency count: Java

```
public class freqhash {
  public static void main(String args[]) throws IOException {
    FileReader f1 = new FileReader(args[0]);
    BufferedReader f2 = new BufferedReader(f1);

    Map<String, Integer> hs = new HashMap<String,Integer>();
    String buf;
    while ((buf = f2.readLine()) != null) {
      String nv[] = buf.split("[   ]+");
      for (int i = 0; i < nv.length; i++) {
        Integer oldv = hs.get(nv[i]);
        if (oldv == null)
          hs.put(nv[i], 1);
        else
          hs.put(nv[i], oldv+1);
      }
    }
    for (String n : hs.keySet()) {
      Integer v = hs.get(n);
      System.out.println(n + " " + v);
    }
  }
}
```

Sorting in Java and C++

```
String s;
List<string> al = new ArrayList<string>();
while ((s = f2.readLine()) != null)
    al.add(s);
Collections.sort(al);
for (String j : al)
    System.out.println(j);
```

```
string tmp;
vector<string> v;
while (getline(cin, tmp))
    v.push_back(tmp);
sort(v.begin(), v.end());
copy(v.begin(), v.end(),
        ostream_iterator<string>(cout,"\n"));
```

What to use, what not to use?

- **Use**
  - classes
  - const
  - const references
  - default constructors
  - C++ -style casts
  - bool
  - new / delete
  - C++ string type
  - range for
  - auto

- **Use sparingly / cautiously**
  - overloaded functions
  - inheritance
  - virtual functions
  - exceptions
  - STL

- **Don't use**
  - malloc / free
  - multiple inheritance
  - run time type identification
  - references if not const
  - overloaded operators (except for arithmetic types)
  - default arguments (overload functions instead)