Life cycle of an object

- **construction and initialization**
  - happens by declaration
    stack s;
  - or explicit call of **new**
    stack *sp = new stack();
  - includes initialization
    different constructors specify different ways to initialize
    default constructor called for arrays
  - copy constructor is an important special case
    specifies how to make a new object from an existing one
    implicitly invoked in declarations, functions arguments, and function return
- **assignment: changing value**
  - by explicitly assigning another object
    obj1 = obj2;
  - assignment is not the same as initialization
- **destruction**
  - reclaim resources
  - must call **delete** explicitly if allocated by **new**
    delete sp;   // or delete [] sp for an array
  - happens implicitly by going out of scope otherwise
    return from function or exit from block

Strings

- **another type that *C* (and *C++*) don't provide**
- **implementation of a string class brings together all of these…**
  - constructors, destructors
    copy constructor
  - assignment versus construction
    operator =
  - constant references
  - handles
  - reference counts, garbage collection
- **an example of a non-trivial data type**

Desirable properties for a string class

- **behave like strings in Awk, Perl, Java**
  - like first-class citizens

- **can easily assign to a string, copy a string, etc.**
- **can pass them to functions, return as results, …**

- **create from "..." C char* strings**
- **can pass them to functions expecting char* 's**

- **storage managed automatically**
  - no explicit allocation or deletion
  - grow and shrink automatically
  - efficient

- **would be nice to have other operations like**
  - substring, search, tokenization, etc.

Copy constructor

- **a constructor that creates an object of class X from an existing object of class X**
- **first try:**

```
class X {
    X(X); // copy constructor?
    // ...
};
```

- **notice a potential problem???**

- **parameter to copy constructor has to be a reference**
  - so it can access the object without copying it

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

String::String(const String& s) { … }
```

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

Initial version of string class

```
class String {
   private:
    char    *sp;
    char    *dup(const char *);

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

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

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

char *String::dup(const char *s) {
    sp = new char[strlen(s) + 1];   // bug: unchecked
    return strcpy(sp, s);
}
```

Potential problems...

- **whole lot of copying going on**
  - each constructor allocates a new string
  - may affect efficiency
- **string assignment is not yet specified**
  - what does this mean?

```
String s1, s2;
s1 = s2;
```

- **want to permit multiple assignment s1 = s2 = s3**

- **assignment is not the same as initialization**
- **the meaning of assignment is defined by a member function named operator=**

```
class String {
    String& operator=(const String&);
    String& operator=(const char *);
    // …
 };
```

- **" x = y " means " x.operator=(y) "**
- **returning a reference permits multiple assignment**

Easy case: string = "..."

- **implementation of operator=(char *)**

```
String& String::operator =(const char *t)
                            // s = "abc"
{
    delete [] sp;
    dup(t);
    return *this;
}
```

- **within a member function, `this` points to the current object, so `*this` is a reference to the object**

- **assignment operators almost always end with**
  `return *this`
  which returns a reference to the LHS, for consistency with built-in assignment (a = b = c)

Harder case: str = str

- **implementation of operator=(const String&)**

- **check if left and right operands are same object**
  - to be sure we don't delete something before using it!
- **do the assignment**
  - often like destruction + copy constructor
- **return the left-hand side**

```
String& String::operator=(const String&t)
{
      if (this != &t) {
            delete [] sp;
            dup(t.sp);
      }
      return *this;
}
```

String class complete

```
class String {
   private:
    char    *sp;
    char    *dup(const char *);

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

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

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

char *String::dup(const char *s) {
    sp = new char[strlen(s) + 1];
    return strcpy(sp, s);
}
```

continued

```
String& String::operator =(const char *s) {
        if (sp != s) {
                delete sp;
                dup(s);
        }
        return *this;
}

String& String::operator =(const String &t) {
    if (this != &t) {
        delete sp;
        dup(t.sp);
    }
    return *this;
}

main() {
    String s = "abc", t = "def", u = s;
    printf("%s %s %s\n", s.s(), t.s(), u.s());
    s = "1234";
    s = s;
    printf("%s\n", s.s());
    s = t = u = "asdf";
    printf("%s %s %s\n", s.s(), t.s(), u.s());
}
```

Handles and use counts

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

- **default copy and assignment allocate new memory even if unnecessary**
  - e.g., in f(const String& s), argument is 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**
  - data pointer
  - counter of how many Strings point to that data
  - when String is copied, increment the use count
  - when String is destroyed, decrement the use count
  - when last use is done, free the characters

  - picture

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

Use counts

```
class Srep {    // string representation
        char *sp;        // data
        int   n;         // ref count
        Srep(const char *);
        friend class String;
};

Srep::Srep(const char *s) {
        if (s == NULL)
                s = "";
        sp = new char[strlen(s) + 1];
        strcpy(sp, s);
        n = 1;
}

class String {
        Srep *p;
   public:
        String(const char *);
        String(const String &);
        ~String();

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

        char *s() { return p->sp; }
};
```

part 2

```
String::String(const char *s = "")
{                           // String s="abc"; String s1;
        p = new Srep(s);
}

String::String(const String &t)     // String s=t;
{
        t.p->n++;       // ref count
        p = t.p;
}

String::~String()
{
        if (--p->n <= 0) {
                delete [] p->sp;
                delete p;
        }
}
```

part 3

```
String& String::operator =(const char *s)
{
        if (p->n > 1) {         // disconnect self
                p->n--;
                p = new Srep(s);
        } else {
                delete [] p->sp;    // free old String
                p->sp = new char[strlen(s) + 1];
                strcpy(p->sp, s);
        }
        return *this;
}

String& String::operator =(const String &t)
{
        t.p->n++;       // protect against s = s
        if (--p->n <= 0) {  // nobody else using me now
                delete [] p->sp;
                delete p;
        }
        p = t.p;
        return *this;
}
```

Rules / heuristics

- **all objects have to have a constructor**
  - if you don't specify a constructor the default constructor copies members by their constructors
  - need a no-argument constructor for arrays
  - constructors should initialize all members

- **if constructor calls new, destructor must call delete**
  - use **delete [ ]** for an array allocated with **new T[n]**

- **copy constructor X(const X&) makes an object**
  - from another one without making an extra copy

- **if there's a complicated constructor**
  - there will have to be an assignment operator
  - make sure that x = x works

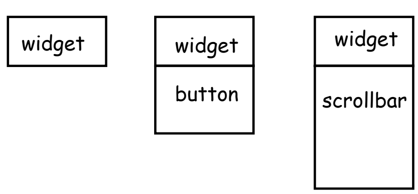
- **assignment is NOT the same as construction**
  - constructors called in declarations, function arguments and function returns, to make a new object
  - assignments called only in assignment statements
    to clobber an existing object

Base & derived classes

```
class Widget {
    int bgcolor;
    // other vars common to all Widgets
};
class Scrollbar : public Widget {
    int min, max, current;
    // other vars specific to Scrollbars
};
```

- **a Scrollbar is a (kind of) Widget**
  - inherits all members of Widget
  - adds its own members

" : public Widget " means public base class members are public in derived as well
  - **protected** means derived class can see but not others



Derived classes

- **derived classes can add their own data members**
- **can add their own member functions**
- **can override base-class functions of the same name and argument types**

```
class Scrollbar : public Widget {
  private:
    int min, max, current;
  public:
    draw() { ... }
    setslider(int) {}
};
class CheckButton : public Widget {
  private:
    bool checked;
  public:
    draw() { ... }
    setstate(bool) { ... }
};
```

```
   CheckButton b; Scrollbar s;
   b.draw();  // call CheckButton::draw
   s.draw();  // call Scrollbar::draw
```

Virtual Functions

- **what if we have bunch of different Widgets and want to draw them all in a loop?**
- **virtual function mechanism lets each object carry information about what functions to apply**

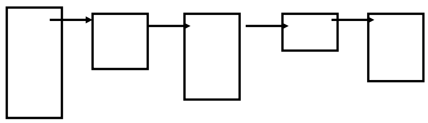
```
class Widget {
  private:
    String caption;
  public:
    setcaption(String c) { caption = c; }

    virtual draw();
    virtual update();
};
```

- **"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**
- **base class can provide a default implementation**
- **a "pure" base class must be derived from**
  - can't exist on its own
  - indicated by " = **0** " on a virtual function declaration

Dynamic binding and virtual functions

- when a pointer or reference to a base-class type points to a derived-class object
- and you use that pointer/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 Widgets on a linked list:

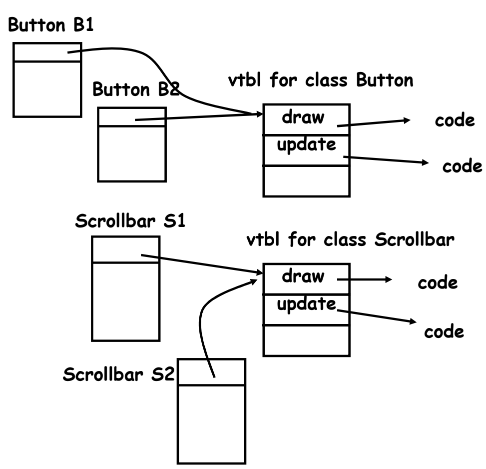
```
draw_all(Widget *p) {
    for ( ; p != NULL; p = p->next)
        p->draw();
}
```



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

Implementation of virtual functions

- each class object has one extra word that holds a pointer to a table of virtual function pointers ("vtbl") (only if class has virtual functions)
- 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 an (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**
    updating different Widgets 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) {
      if (n < 0 || n >= size)
           assert(n >= 0 && n < size);
      else
           return v[n]; }
    T& elem(int n) { 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
```

Template functions

- **can define ordinary functions as templates**
- **e.g., max(T, T)**

```
template <typename T> T max(T x, T y)
{
  return x > y ? x : y;
}
```

- **requires operator> for type T**
  already there for C's arithmetic types
- **don't need a type name to use it**
  compiler infers types from arguments
    max(double, double)
    max(int, int)
    // max(int, double) doesn't compile: no coercion
- **compiler instantiates code for each different use in a program**

Scoped pointer class

```
// scoped pointer class
// allocates space when used, frees it
  automatically when deleted

#include <stdio.h>

struct foo { int x; double y; };

template <typename X> class SP {
   X *xp;
 public:
   SP(X *p) : xp(p) {}
   ~SP() { printf("deleting\n"); delete xp; }
   X* operator ->() { return xp; }
};

int main() {
   printf("top\n");
   {
       SP<struct foo> foop(new struct foo);
       foop->x = 1;
       foop->y = 2.3;
   }
   printf("bot\n");
}
```

Standard Template Library (STL)

Alex Stepanov

(GE > Bell Labs > HP > SGI -> Compaq -> Adobe)

- **general-purpose library of**
  - **generic algorithms (find, replace, sort, …)**
  - **containers (vector, list, set, map, …)**
- **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<…>
- **iterator: generalization of a pointer**
- **performance guarantees**
  - each combination of algorithm and iterator type specifies worst-case (O(…)) performance bound
    - e.g., maps are O(log n) access

Containers and algorithms

- **STL container classes contain objects of any type**
  - sequences: vector, list, slist, deque
  - sorted associative: set, map, multiset, multimap
    - hash_set and hash_map are non-standard
- **each 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, …

Iterators

- **a generalization of C pointers**
- **a 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**
- **basic loop:**

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

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

Example 1

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

int main() {  // sort stdin by lines
    vector<string> v;
    string tmp;

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

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

  `sort(v.begin(), v.end(), greater<string>())`

  would sort in decreasing order

Function objects

- **anything that can be applied to zero or more arguments to get a value and/or change the state of a computation**
- **can be an ordinary function pointer**
- **can be an object of a type defined by a class in which the function call operator [operator ( )] is overloaded**

```
template <typename T> class greater {
  public:
  bool operator()(T const& x, T const& y)
  {
      return x > y;
  }
};
```

Iterator example

- STL copy algorithm
- satisfies constraints on iterators

```
template <typename InputIterator,
            typename OutputIterator>
OutputIterator mycopy(InputIterator first,
   InputIterator last, OutputIterator result)
{
    while (first != last)
        *result++ = *first++;
    return result;
}

main() {
    vector<int> v;

    for (int i = 0; i < 10; i++)
        v.push_back(i);
    mycopy(v.begin(), v.end(),
        ostream_iterator<int>(cout, "\n"));
}
```

Should I use the STL?

- code is often extremely clean and elegant
- usually easy to change underlying data structure
- often runs slow, sometimes extremely slow
- implementations are getting better

```
#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 (i = v.begin(); i != v.end(); ++i)
        cout << i->first << " "
             << i->second << "\n";
}
```

Sorting: Java v. C++

```
String s;
List al = new ArrayList();
while ((s = f2.readLine()) != null)
    al.add(s);
Collections.sort(al);
for (int j = 0; j < al.size(); j++)
    System.out.println(al.get(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"));
```

Add up the numbers: Java v. C++

```
while ((buf = f2.readLine()) != null) {
    String nv[] = buf.split("[     ]+");
    for (int i = 0; i < nv.length; i++) {
        try {
            double d =
               Double.parseDouble(nv[i]);
            dsum += d;
        } catch (NumberFormatException e) {
            ;
        }
    }
}
```

```
while (getline(cin, tmp)) {
    istringstream iss(tmp);
    vector<double> v;
    double d;
    string s;
    while (iss >> s) {
        d = atof(s.c_str());
        v.push_back(d);
        dsum += d;
    }
}
```

Matrix transpose: Java

```
String buf;
List mat = new ArrayList();
for (int r=0; (buf = f2.readLine())!=null; r++)
    String nv[] = buf.split("[     ]+");
    for (int c = 0; c < nv.length; c++) {
        if (r == 0)
            mat.add(new ArrayList());
        ((List) mat.get(c)).add(nv[c]);
    }
}
for (int i = 0; i < mat.size(); i++) {
    StringBuffer sb = new StringBuffer();
    List ls = ((List) mat.get(i));
    int jmax = ls.size();
    for (int j = 0; j < jmax; j++)
        sb.append(ls.get(j)).append(" ");
    System.out.println(sb);
}
```

Matrix transpose: C++ STL

```
string tmp;
vector<vector<string> > mat;
for (int r = 0; (getline(cin, tmp); r++) {
    istringstream iss(tmp);
    string s;
    vector<string> v;
    for (int c = 0; iss >> s; c++) {
        if (r == 0)
            mat.push_back(v);
        mat[c].push_back(s);
    }
}
for (int i = 0; i < mat.size(); i++) {
    copy(mat[i].begin(), mat[i].end(),
        ostream_iterator<string>(cout, " "));
    cout << "\n";
}
```

Exception handling

- **necessary so libraries can propagate errors back to users**

```
class ivec {
    int *v;         // pointer to array
    int size;    // number of elements
  public:
    int &operator [](int n);
    //...
};

int& ivec::operator [](int n) {
    if (n < 0 || n >= size)
        throw(subscriptrange(n));
    else
        return v[n];
}

int f() {
    ivec iv(100);
    try {
        return g(iv);   // normal return if no exceptions
    }
    catch (subscriptrange) {
        return 0;  // get here if `subscriptrange' was
                   // raised in g() or anything it calls
    }
    catch (...) {        // get here if some other
        return -1;       // exception was raised
    }
}
```

C++ reprise: things to remember

- **abstraction: separating <u>what</u> from <u>how</u>**
  - creating internal firewalls and barriers in code
  - separating interface from implementation
- **classes are user-defined types**
  - they should model objects in the application
- **object-oriented programming**
  - public methods define interface to the world
  - private methods and members for implementation
  - overloading functions and operators
- **constructors, assignment operators, destructors**
  - complete control over creation, copying, deletion
  - references provide access without copying
- **inheritance to describe family of related types**
  - base and derived classes
  - polymorphism to call the right functions dynamically
- **templates and parameterized types**
  - generic algorithms, container classes, iterators

What to use, what not to use?

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