Object-Oriented Design and Programming

C++ Language Support for Abstract Data Types

Douglas C. Schmidt

www.cs.wustl.edu/~schmidt/

schmidt@cs.wustl.edu

Washington University, St. Louis

Describing Objects Using ADTs

- An abstract data type (ADT) is a set of objects and an associated set of operations on those objects

- ADTs support *abstraction*, *encapsulation*, and *information hiding*

  – Basically, enhance representational independence...

- They provide equal attention to data *and* operations

- Common examples of ADTs:

  – *Built-in types*: **boolean**, **integer**, **real**, **arrays**

  – *User-defined types*: **stacks**, **queues**, **trees**, **lists**

Built-in ADTs

- **boolean**
  - *Values*: TRUE and FALSE
  - *Operations*: **`and`**, **`or`**, **`not`**, **`nand`**, etc.

- **integer**
  - *Values*: Whole numbers between MIN and MAX values
  - *Operations*: **`add`**, **`subtract`**, **`multiply`**, **`divide`**, etc.

- **arrays**
  - *Values*: Homogeneous elements, *i.e.*, array of *X*...
  - *Operations*: **`initialize`**, **`store`**, **`retrieve`**, **`copy`**, etc.

User-defined ADTs

- **stack**
  - *Values*: Stack elements, *i.e.*, stack of X...
  - *Operations*: **`create, dispose, push, pop, is_empty, is_full`**, etc.

- **queue**
  - *Values*: Queue elements, *i.e.*, queue of X...
  - *Operations*: **`create, dispose, enqueue, dequeue, is_empty, is_full`**, etc.

- **tree search structure**
  - *Values*: Tree elements, *i.e.*, tree of X
  - *Operations*: **`insert, delete, find, size, traverse (in-order, post-order, pre-order, level-order)`**, etc.

Avoiding Over-Specification

- *Goal*:
  - We want complete, precise, and unambiguous descriptions and specifications of software components

- *Problem*:
  - We do *not* want to be dependent on physical representation
    * Too hard to port
    * Too hard to change implementation

- *Solution*
  - Use ADTs
    * ADTs capture essential properties without over-specifying their internal realizations
    * ADT interfaces provide a list of *operations* rather than an implementation description
      · *i.e.*, *what* rather than *how*

Over-Specification Examples

- *e.g.*,

```
int buffer[100], last = −1;
...
buffer[++last] = 13;
```

- *e.g.*,

```
struct Node {
     int item_;
     Node *next_;
} *p, *first = 0;
...
p = new Node;
p->next_ = first; p->item_ = 13; first = p;
```

- *e.g.*,

```
template <class T, int SIZE>
class Stack {
public:
     int push (T new_item); /* ...*/
     // ...
private:
     T stack_[SIZE]
};
Stack<int, 100> int_stack;
// ...
int_stack.push (13);
```

Algebraic Specification of ADTs

- Allows complete, precise, and non-ambiguous specification of ADTs without over-specifying their underlying implementation
  - *e.g.*, language independent

- ADT specification techniques must define:
  - *Syntax*
    - *e.g.*, map function: arguments $\rightarrow$ results
  - *Semantics*
    - Meaning of the mapping
    - Often entails preconditions, postconditions, axioms
  - *Exceptions*
    - Error conditions

Algebraic Specification of ADTs (cont'd)

- Algebraic specifications attempt to be complete, consistent, and handle errors
  - They consist of four parts: *types*, *functions*, *preconditions/postconditions*, and *axioms*
    - *e.g.*,

types
    STACK[T]
functions
    create: $\rightarrow$ STACK[T]
    push: STACK[T] $\times$ T $\rightarrow$ STACK[T]
    pop: STACK[T] $\rightarrow$ STACK[T]
    top: STACK[T] $\rightarrow$ T
    empty: STACK[T] $\rightarrow$ BOOLEAN
    full: STACK[T] $\rightarrow$ BOOLEAN
preconditions/postconditions
    pre *pop* (*s*: STACK[T]) = (**not** *empty* (*s*))
    pre *top* (*s*: STACK[T]) = (**not** *empty* (*s*))
    pre *push* (*s*: STACK[T], *i*: T) = (**not** *full* (*s*))
    post *push* (*s*: STACK[T], *i* : T) = (**not** *empty* (*s*)
axioms
    for all *t*: T, *s*: STACK[T]:
        empty (*create* ())
        not *empty* (*push* (*t*, *s*))
        top (*push* (*s*, *t*)) = *t*
        pop (*push* (*s*, *t*)) = *s*

Eiffel Stack Example

- -- Implement a bounded stack abstraction in Eiffel

```
class STACK[T] export
      is_empty, is_full, push, pop, top
feature
      buffer : ARRAY[T];
      top_ : INTEGER;
      Create (n : INTEGER) is
            do
                  top_ := 0;
                  buffer.Create (1, n);
            end; -- Create
      is_empty: BOOLEAN is
            do
                  Result := top_ <= 0;
            end; -- is_empty
      is_full: BOOLEAN is
            do
                  Result := top_ >= buffer.size;
            end; -- is_full
      top: T is
            require
                  not is_empty
            do
                  Result := buffer.entry (top_);
            end; -- pop
```

Eiffel Stack Example (cont'd)

- *e.g.*,

```
    pop: T is
        require
            not is_empty
        do
            Result := buffer.entry (top_);
            top_ := top_ − 1;
        ensure
            not is_full;
            top_ = old top_ − 1;
        end; -- pop
    push (x : T) is
        require
            not is_full;
        do
            top_ := top_ + 1;
            buffer.enter (top_, x);
        ensure
            not is_empty; top = x;
            top_ = old top_ + 1;
        end; -- push
    invariant
        top_ >= 0 and top_ < buffer.size;
end; -- class STACK
```

Eiffel Stack Example (cont'd)

- *e.g.*, An Eiffel program used to reverse a name

```
class main feature
      MAX_NAME_LEN : INTEGER is 80;
      MAX_STACK_SIZE : INTEGER is 80;
Create is
      local
            io : STD_FILES;
            st : STACK[CHARACTER];
            str : STRING;
            index : INTEGER;
      do
            io.create; str.create (MAX_NAME_LEN);
            st.create (MAX_STACK_SIZE);
            io.output.putstring ("enter your name..: ");
            io.input.readstring (MAX_NAME_LEN);
            str := io.input.laststring;
            from index := 1;
            until index > str.length or st.is_full
            loop
                  st.push (str.entry (index));
                  index := index + 1;
            end;

            from until st.is_empty loop
                  io.output.putchar (st.pop);
            end;
            io.output.new_line;
      end;
end;
```

C++ Support for ADTs

- *C++ Classes*
- *Automatic Initialization and Termination*
- *Assignment and Initialization*
- *Parameterized Types*
- *Exception Handling*
- *Iterators*

C++ Classes

- A C++ **class** is an extension to the **struct** type specifier in C

- Classes are *containers* for **state variables** and provide **operations** (*i.e.*, *methods*) for manipulating the state variables

- A **class** is separated into three *access control sections*:

```
class Classic_Example {
public:
     // Data and methods accessible to
     // any user of the class
protected:
     // Data and methods accessible to
     // class methods, derived classes, and
     // friends only
private:
     // Data and methods accessible to class
     // methods and friends only
};
```

C++ Classes (cont'd)

- Each access control section is optional, repeatable, and sections may occur in any order

- Note, access control section order may affect storage layout for classes and structs:
  - C++ only guarantees that consecutive fields appear at ascending addresses *within* a section, not *between* sections, *e.g.*,

```
class Foo { /* Compiler may not rearrange these! */
     int a_;
     char b_;
     double c_;
     char d_;
     float e_;
     short f_;
};
class Foo { /* Compile may rearrange these! */
public: int a_;
public: char b_;
public: double c_;
public: char d_;
public: float e_;
public: short f_;
};
```

C++ Classes (cont'd)

- By default, all **class** members are private and all **struct** members are **public**
  - A **struct** is interpreted as a **class** with all data objects and methods declared in the public section

- A class definition does *not* allocate storage for any objects
  - *i.e.*, it is just a cookie cutter...
  - Remember this when we talk about nested classes...
  - Note, a class with virtual methods will allocate at least one *vtable* to store virtual method definitions

C++ Class Components

- *Nested classes, structs, unions, and enumerated types*
  - Versions of AT&T cfront translator later than 2.1 enforce proper class nesting semantics

- *Data Members*
  - Including both built-in types and user-defined class objects

- *Methods*
  - Also called "member functions," only these operations (and friends) may access private class data and operations

C++ Class Components (cont'd)

- The *this* pointer
  - Used in the source code to refer to a pointer to the object for which the method is called

- *Friends*
  - Non-class functions granted privileges to access internal class information, typically for efficiency reasons

Nested Classes et al.

- Earlier releases of C++ (*i.e.*, cfront versions pre–2.1) did not support nested semantics of nested classes
  - *i.e.*, nesting was only a syntactic convenience

- This was a problem since it prevented control over name space pollution of type names
  - Compare with **static** for functions and variables

- It is now possible to fully nest classes and structs
  - Class visibility is subject to normal access control...

- Note, the new C++ namespace feature is a more general solution to this problem...

Nested Classes et al. (cont'd)

- *e.g.*,

```
class Outer {
public:
    class Visible_Inner { /* ...*/ };
private:
    class Hidden_Inner { /* ...*/ };
};

Outer outer; /* OK */
Hidden_Inner hi; /* ERROR */
Visible_Inner vi; /* ERROR */
Outer::Visible_Inner ovi; /* OK */
Outer::Hidden_Inner ohi; /* ERROR */
```

- Note,
  - Nesting is purely a visibility issue, it does not convey additional privileges on Outer or Inner class relationships
    - *i.e.*, nesting and access control are separate concepts
  - Also, inner classes do *not* allocate any additional space inside the outer class

Class Data Members

- Data members may be objects of built-in types, as well as user-defined types, *e.g.*, class Bounded_Stack

```
#include "Vector.h"
template <class T>
class Bounded_Stack {
public:
     Bounded_Stack (int len): stack_ (len), top_ (0) {}
     void push (T new_item) {
          this->stack_[this->top_++] = new_item;
     }
     T pop (void) { return this->stack_[--this->top_]; }
     T top (void) const {
          return this->stack_[this->top_ - 1]; }
     int is_empty (void) const { return this->top_ == 0; }
     int is_full (void) const {
          return this->top_ >= this->stack_.size ();
     }
private:
     Vector<T> stack_;
     int top_;
};
```

Class Data Members (cont'd)

- Important Question: "How do we initialize class data members that are objects of user-defined types whose constructors require arguments?"

- Answer: use the *base/member initialization* section
  - That's the part of the constructor after the ':', following the constructor's parameter list (up to the first '{')

- Note, it is a good habit to always use the base/member initialization section
  - *e.g.*, there are less efficiency surprises this way when changes are made

- Base/member initialization section only applies to constructors

Base/Member Initialization Section

- Four mandatory cases for classes:

  1. Initializing base classes (whose constructors require arguments)

  2. Initializing user-defined class data members (whose constructors require arguments)

  3. Initializing reference variables

  4. Initializing **const**s

- One optional case:

  1. Initializing built-in data members

Base/Member Initialization Section (cont'd)

- *e.g.*,

```
class Vector { public: Vector (size_t len); /* ...*/ };
class String { public: String (char *str); /* ...*/ };
class Stack : private Vector // Base class
{
public:
     Stack (size_t len, char *name)
          : Vector (len), name_ (name),
               MAX_SIZE_ (len), top_ (0) {}
     // ...
private:
     String name_; // user-defined
     const int MAX_SIZE_; // const
     size_t top_; // built-in type
     // ...
};
class Vector_Iterator {
public:
     Vector_Iterator (const Vector &v): vr_ (v), i_ (0) {}
     // ...
private:
     Vector &vr_; // reference
     size_t i_;
};
```

Class Methods

- Four types of methods

  1. *Manager functions* (constructors, destructors, and **operator=**)

     – Allow user-defined control over class creation, initialization, assignment, deallocation, and termination

  2. *Helper functions*

     – "Hidden" functions that assist in the class implementation

  3. *Accessor functions*

     – Provide an interface to various components in the class's state

  4. *Implementor functions*

     – Perform the main class operations

Class Methods (cont'd)

- *e.g.*,

```
// typedef int T;
template <class T>
class Vector
{
public:
     // manager
     Vector (size_t len_ = 100);

     // manager
     ~Vector (void);

     // accessor
     size_t size (void) const;

     // implementor
     T &operator[] (size_t i);

private:
     // helper
     bool in_range (size_t i) const;
};
```

The this Pointer

- **this** is a C++ reserved keyword
  - It valid only in non-**static** method definitions

- **this** textually identifies the pointer to the object for which the method is called

```
class String {
public:
     void print (void);
     // ...
private:
     char *str_;
     // ...
};
void String::print (void) {
     puts (this->str_); // same as puts (str_);
}
int main (void) {
     String s, t;
     s.print (); // this == &s
     t.print (); // this == &t
}
```

The this Pointer (cont'd)

- The **this** pointer is most often used explicitly to
  - Pass the object (or a pointer or reference to it) to another function
  - Return the object (or a pointer or reference to it) to another function, *e.g.*,

```
#include <ctype.h>
class String {
public:
     String &upper_case (void);
     void print (void) const;
private:
     char *str_;
};
String &String::upper_case (void) {
     for (char *cp = this->str_; *cp != 0; cp++)
          if (islower (*cp))
               *cp = toupper (*cp);
     return *this;
}
int main (void) {
     String s ("hello"); // this == &s
     s.upper_case ().print ();
     /* Could also be:
          s.upper_case ();
          s.print ();
     compare with:
          cout << s.upper_case ();
          */
}
```

Friends

- A class may grant access to its private data and methods by including a list of *friends* in the class definition, *e.g.*,

```
class Vector {
friend Vector &product (const Vector &, const &Matrix);
private:
    int size_;
    // ...
};
class Matrix {
friend Vector &product (const Vector &, const &Matrix);
private:
    int size_;
    // ...
};
```

- Function `product` can now access private parts of both the `Vector` and `Matrix`, allowing faster access, *e.g.*,

```
Vector &product (const Vector &v, const Matrix &m) {
    int vector_size = v.size_;
    int matrix_size = m.size_;
    // ...
}
```

Friends (cont'd)

- Note, a class may confer friendship on the following:

  1. *Entire classes*
  2. *Selected methods in a particular class*
  3. *Ordinary stand-alone functions*

- Friends allow for controlled violation of information-hiding

  – *e.g.*, ostream and istream functions:

```
#include <iostream.h>
class String {
friend ostream &operator << (ostream &, String &);
private:
     char *str_;
// ...
};

ostream &operator << (ostream &os, String &s) {
     os << s.str_;
     return os;
}
```

Friends (cont'd)

- Using **friend**s weakens information hiding
  - In particular, it leads to tightly-coupled implementations that are overly reliant on certain *naming* and *implementation* details
- For this reason, **friend**s are known as the "goto of access protection mechanisms!"
- Note, C++ **inline** functions reduce the need for **friend**s...

Class Vector Example

- // File Vector.h (correct wrt initialization and assignment)

```
// typedef int T;
template <class T>
class Vector
{
public:
      ~Vector (void);
      Vector (size_t len = 100, const T init = 0);
      size_t size (void) const;
      T &operator[] (size_t i);
      /* New functions */
      Vector (const Vector<T> &v); // Copy constructor
      // Assignment operator
      Vector<T> &operator= (const Vector<T> &v);
protected:
      T &elem (size_t i);
private:
      size_t size_;
      size_t max_;
      T *buf_;
      bool in_range (size_t i);
};
```

- This class solves previous problems with aliasing and deletion...

Initialization and Termination

- Automatic initialization and termination activities are supported in C++ via constructors and destructors

- *Constructors*

  – Allocate data objects upon creation

  – Initialize class data members

  – *e.g.*,

```
template <class T>
Vector<T>::Vector (size_t len, const T init)
          : size_ (len), max_ (len)
{
     if (this->size_ <= 0)
          throw Vector<T>::RANGE_ERROR ();

     this->buf_ = new T[this->size_];

     while (--this->size_ >= 0)
          this->buf_[this->size_] = init;

     if (verbose_logging)
          log ("constructing Vector object");
}
```

Initialization and Termination (cont'd)

- *Destructors*
  - Deallocate data allocated by the constructor
  - Perform other tasks associated with object termination
  - *e.g.*,

```
template <class T>
Vector<T>::~Vector (void) {
    delete [] this->buf_;

    if (verbose_logging)
        log ("destructing Vector object");
}
```

Initialization and Termination (cont'd)

- Without exceptions, handling constructor or destructor failures is very difficult and/or ugly, *e.g.*,

  1. Abort entire program

  2. Set global (or class instance) flag

  3. Return reference parameter (works for constructors, but not destructors)

  4. Log message and continue...

- However, exceptions have their own traps and pitfalls...

Assignment and Initialization

- Some ADTs must control all copy operations invoked upon objects

- This is necessary to avoid dynamic memory aliasing problems caused by "shallow" copying

- A String class is a good example of the need for controlling all copy operations...

Assignment and Initialization (cont'd)

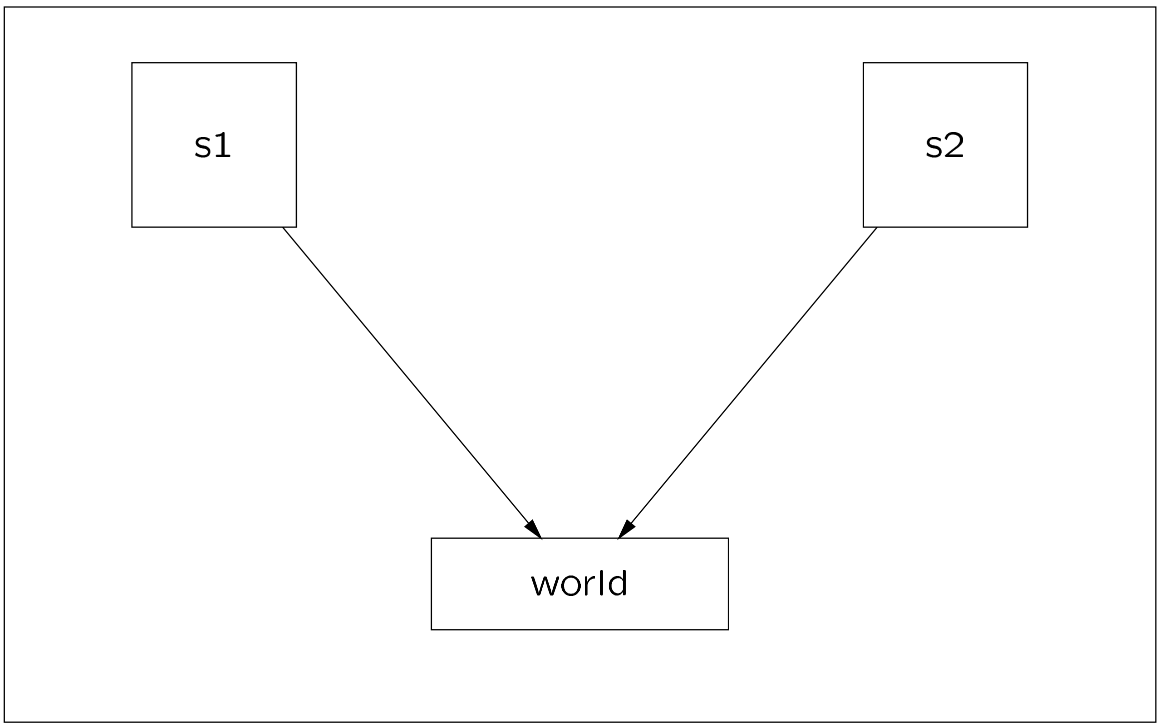
- *e.g.*,

```
class String {
public:
     String (char *t)
          : len_ (t == 0 ? 0 : ::strlen (t)) {
          if (this->len_ == 0)
               throw RANGE_ERROR ();
          this->str_ = ::strcpy (new char [len_ + 1], t);
     }
     ~String (void) { delete [] this->str_; }
     // ...
private:
     size_t len_, char *str_;
};

void foo (void) {
     String s1 ("hello");
     String s2 ("world");

     s1 = s2; // leads to aliasing
     s1[2] = 'x';
     assert (s2[2] == 'x'); // will be true!
     // ...
     // double deletion in destructor calls!
}
```

Assignment and Initialization (cont'd)



- Note that both s1.s and s2.s point to the dynamically allocated buffer storing "world" (this is known as "aliasing")

Assignment and Initialization (cont'd)

- In C++, copy operations include assignment, initialization, parameter passing and function return, *e.g.*,

```
#include "Vector.h"

extern Vector<int> bar (Vector<int>);

void foo (void) {
     Vector<int> v1 (100);

     Vector<int> v2 = v1; // Initialize new v2 from v1
                          // same as Vector v2 (v1);

     v1 = v2; // Vector assign v2 to v1

     v2 = bar (v1); // Pass and return Vectors
}
```

- Note, parameter passing and function return of objects by *value* is treated using initialization semantics via the "copy constructor"

Assignment and Initialization (cont'd)

- Assignment is different than initialization, since the left hand object already exists for assignment

- Therefore, C++ provides two related, but different operators, one for initialization (the copy constructor, which also handles parameter passing and return of objects from functions)...

```
template <class T>
Vector<T>::Vector (const Vector &v)
    : size_ (v.size_), max_ (v.max), buf_ (new T[v.max])
{
    for (size_t i = 0; i < this->size_; i++)
        this->buf_[i] = v.buf_[i];
    if (verbose_logging)
        log ("initializing Vector object");
}
```

Assignment and Initialization (cont'd)

- ...and one for assignment (the assignment operator), *e.g.*,

```
template <class T>
Vector<T> &Vector<T>::operator= (const Vector<T> &v)
{
     if (this != &v) {
          if (this->max_ < v.size_) {
               delete [] this->buf_;
               this->buf_ = new T[v.size_];
               this->max_ = v.size_;
          }
          this->size_ = v.size_;

          for (size_t i = 0; i < this->size_; i++)
               this->buf_[i] = v.buf_[i];
     }
     return *this; // Allows v1 = v2 = v3;
}
```

Assignment and Initialization (cont'd)

- Both constructors and **operator** = must be class members and neither are inherited
  - Rationale
    * If a class had a constructor and an **operator** =, but a class derived from it did not what would happen to the derived class members which are not part of the base class?!
  - Therefore
    * If a constructor or **operator** = is *not* defined for the derived class, the compiler-generated one will use the base class constructors and **operator** ='s for each base class (whether user-defined or compiler-defined)
    * In addition, a memberwise copy (*e.g.*, using **operator** =) is used for each of the derived class members

Assignment and Initialization (cont'd)

- Bottom-line: define constructors and **operator=** for almost every non-trivial class...
  - Also, define destructors and copy constructors for most classes as well...

- Note, you can also define compound assignment operators, such as **operator +=**, which need have nothing to do with **operator =**

Vector Usage Example

- // File main.C

```
#include <stream.h>
#include "Vector.h"

extern atoi (char *);

int main (int argc, char *argv[]) {
     int size = argc > 1 ? ::atoi (argv[1]) : 10;
     Vector<int> v1 (size); // defaults to 0
     Vector<int> v2 (v1);
     /* or:
          Vector<int> v2 = v1;
          Vector<int> v2 = Vector<int> (v1);
          Vector<int> v2 = (Vector<int>) v1; */

     ::srandom (::time (0L));

     for (size_t i = 0; i < v1.size (); i++)
          v1[i] = v2[i] = ::random ();

     Vector<int> v3 (v1.size (), -1);
     /* Perform a Vector assignment */
     v3 = v1;

     for (size_t i = 0; i < v3.size (); i++)
          cout << v3[i];
}
```

Restricting Assignment and Initialization

- Assignment, initialization, and parameter passing of objects by value may be prohibited by using access control specifiers:

```
template <class T>
class Vector {
public:
     Vector<T> (void); // Default constructor
     // ...
private:
     Vector<T> &operator= (const Vector<T> &);
     Vector<T> (const Vector<T> &);
     // ...
}
void foo (Vector<int>); // pass-by-value prototype
Vector<int> v1;
Vector<int> v2 = v1; // Error

v2 = v1; // Error
foo (v1); // Error
```

- Note, these idioms are surprisingly useful...

Restricting Assignment and Initialization (cont'd)

- Note, a similar trick can be used to prevent **static** or **auto** declaration of an object, *i.e.*, only allows dynamic objects!

```
class Foo {
public:
    // ...
    void dispose (void);
private:
    // ...
    ~Foo (void); // Destructor is private...
};
Foo f; // error
```

- Now the only way to declare a Foo object is off the heap, using operator **new**

```
Foo *f = new Foo;
```

- Note, the **delete** operator is no longer accessible

```
    delete f; // error!
```

- Therefore, a `dispose` function must be provided to **delete** this

```
    f->dispose ();
```

Restricting Assignment and Initialization (cont'd)

- If you declare a class constructor **protected** then only objects derived from the class can be created
  - Note, you can also use *pure virtual functions* to achieve a similar effect, though it forces the use of virtual tables...

- *e.g.*,

  class Foo { **protected**: Foo (**void**); };
  class Bar : **private** Foo { **public** Bar (**void**); };
  Foo f; // Illegal
  Bar b; // OK

- Note, if Foo's constructor is declared in the **private** section then we can not declare objects of class Bar either (unless class Bar is declared as a friend of Foo)

Overloading

- C++ allows overloading of all function names and nearly all operators that handle user-defined types, including:
  - the assignment **operator** =
  - the function call **operator** ()
  - the array subscript **operator** []
  - the pointer **operator** ->()
  - the "comma" **operator** ,
  - the auto-increment **operator** ++
- You may not overload:
  - the scope resolution **operator** ::
  - the ternary **operator** ? :
  - the "dot" **operator** .

Overloading (cont'd)

- Ambiguous cases are rejected by the compiler, *e.g.*,

  int foo (**int**);
  int foo (**int**, **int** = 10);
  foo (100); // ERROR, ambiguous call!
  foo (100, 101); // OK!

- A function's return type is not considered when distinguishing between overloaded instances
  - *e.g.*, the following declarations are ambiguous to the C++ compiler:

    extern int divide (**double**, **double**);
    extern double divide (**double**, **double**);

- Overloading becomes a hindrance to the readability of a program when it serves to remove information
  - This is especially true of overloading operators!
    * *e.g.*, overloading operators += and -= to mean push and pop from a Stack ADT

Overloading (cont'd)

- Function name overloading and operator overloading relieves the programmer from the lexical complexity of specifying unique function identifier names. *e.g.*,

```
class String {
     // various constructors, destructors,
     // and methods omitted
     friend String operator+ (String&, const char *);
     friend String operator+ (String&,String&);
     friend String operator+ (const char *, String&);
     friend ostream &operator<< (ostream &, String &);
};
String str_vec[101];
String curly ("curly");
String comma (", ");
str_vec[13] = "larry";
String foo = str_vec[13] + ", " + curly;
String bar = foo + comma + "and moe";
/* bar.String::String (
     operator+ (operator+ (foo, comma), "and moe")); */

void baz (void) {
     cout << bar << "\n";
     // prints "larry, curly, and moe"
}
```

Overloading (cont'd)

- For another example of why to avoid operator overloading, consider the following expression:

```
Matrix a, b, c, d;
// ...
a = b + c * d; // *, +, and = are overloaded
// remember, "standard" precedence rules apply...
```

- This code will be compiled into something like the following:

```
Matrix t1 = c.operator* (d);
Matrix t2 = b.operator+ (t1);
a.operator= (t2);
destroy t1;
destroy t2;
```

- This may involve many constructor/destructor calls and extra memory copying...

Overloading (cont'd)

- There are two issues to consider when *composing* overloaded operators in expressions, *e.g.*,

  - Two issues to

    1. *Memory Management*

       * Creation and destruction of temporary variables

       * Where is memory for return values allocated?

    2. *Error Handling*

       * *e.g.*, what happens if a constructor for a temporary object fails in an expression?

       * This requires some type of exception handling

Overloading (cont'd)

- Bottom-line: do not use operator overloading unless absolutely necessary!

- Instead, many operations may be written using functions with explicit arguments, *e.g.*,

```
Matrix a, b, c, d;
...
Matrix t (b);
t.add (c);
t.mult (d);
a = t;
```

- or define and use the short-hand **operator** x= instead:

```
Matrix a (c);
a *= d;
a += b;
```

- Note that this is the same as

```
a = b + c * d;
```

Parameterized Types

- Parameterized types serve to describe general container class data structures that have identical implementations, regardless of the elements they are composed of

- The C++ parameterized type scheme allows "lazy instantiation"
  - *i.e.*, the compiler need not generate definitions for template methods that are not used

- ANSI/ISO C++ also supports template specifiers, that allow a programmer to "pre-instantiate" certain parameterized types, *e.g.*,

  ```
  template class Vector<int>;
  ```

Parameterized Types

- Here's the Vector class again (this time using a default parameter for the type)

```
template <class T = int>
class Vector
{
public:
     Vector (size_t len): size_ (len),
          buf_ (new T[size_ < 0 ? 1 : size_]) {}
     T &operator[] (size_t i) { return this->buf_[i]; }
     // ...
private;
     size_t size_; /* Note, this must come first!!! */
     T *buf_;
};
Vector<> v1 (20); // int by default...
Vector<String> v2 (30);
typedef Vector<Complex> COMPLEX_VECTOR;
COMPLEX_VECTOR v3 (40);
v1[1] = 20;
v2[3] = "hello";
v3[10] = Complex (1.0, 1.1);
v1[2] = "hello"; // ERROR!
```

Parameterized Types (cont'd)

- *e.g.*,

```
Vector<int> *foo (size_t size) {
    // An array of size number of doubles
    Vector<double> vd (size); // constructor called

    // A dynamically allocated array of size chars
    Vector<char> *vc = new Vector<char>(size);

    // size arrays of 100 ints
    Vector<int> *vi = new Vector<int>[size];

    /* ...*/
    delete vc; /* Destructor for vc called */

    // won't be deallocated until delete is called!
    return vi;
    /* Destructor called for auto variable vd */
}
```

- Usage

```
Vector<int> *va = foo (10);
assert (va[1].size () == 100);
delete [] va; /* Call 10 destructors */
```

Parameterized Types (cont'd)

- Note that we could also use templates to supply the size of a vector at compile-time (more efficient, but less flexible)

```
template <class T = int, size_t SIZE = 100>
class Vector
{
public:
     Vector (void): size_ (SIZE) {}
     T &operator[] (size_t i) { return this->buf_[i]; }
private:
     size_t size_;
     T buf[SIZE];
};
```

- This would be used as follows:

```
Vector<double, 1000> v;
```

Parameterized Types (cont'd)

- C++ templates may also be used to parameterize functions, *e.g.*,

```
template <class T> inline void
swap (T &x, T &y) {
     T t = x;
     x = y;
     y = t;
}

int main (void) {
     int a = 10, b = 20;
     double d = 10.0, e = 20.0;
     char c = 'a', s = 'b';

     swap (a, b);
     swap (d, e);
     swap (c, s);
}
```

- Note that the C++ compiler is responsible for generating all the necessary code...

Exception Handling Overview

- Exception handling provides a disciplined way of dealing with erroneous run-time events

- When used properly, exception handling makes functions easier to understand because they separate out error code from normal control flow

- C++ exceptions may **throw** and **catch** arbitrary C++ objects
  - Therefore, an unlimited amount of information may be passed along with the exception indication

- The *termination* (rather than *resumption*) model of exception handling is used

Limitations of Exception Handling

- Exception handling may be costly in terms of time/space efficiency and portability
  - *e.g.*, it may be inefficient even if exceptions are not used or not raised during a program's execution

- Exception handling is not appropriate for all forms of error-handling, *e.g.*,
  - If immediate handling or precise context is required
  - If "error" case may occur frequently
    - *e.g.*, reaching end of linked list

- Exception handling can be hard to program correctly

Exception Handling Examples

- Without exceptions:

```
Stack s;
int i;
// ...
if (!s.is_full ()) s.push (10);
else /* ...*/
// ...
if (!s.is_empty ()) i = s.pop ();
else /* ...*/
```

- Versus

```
Stack s;
int i;
try { s.push (10);
      // ...
      i = s.pop ();
}
catch (Stack::UNDERFLOW &e) { /* ...*/ }
catch (Stack::OVERFLOW &e) { /* ...*/ }
```

Another C++ Exception Handling Example

- Note the sublte chances for errors...

```
class xxii {
public:
     xxii (const String &r): reason_ (r) {}
     String reason_;
};
int g (const String &s) {
     String null ("");
     if (s == null) throw xxii ("null string");
          // destructors are automatically called!
     // ...
}
int f (const String &s) {
     try {
          String s1 (s);
          char *s2 = new char[100]; // careful...
          // ...
          g (s1);
          delete [] s2;
          return 1;
     }
     catch (xxii &e) {
          cerr << "g() failed, " << e.reason_;
          return 22;
     }
     catch (...) {
          cerr << "unknown error occurred!";
          return -1;
     }
}
```

Iterators

- Iterators allow applications to loop through elements of some ADT without depending upon knowledge of its implementation details

- There are a number of different techniques for implementing iterators
  - Each has advantages and disadvantages

- Other design issues:
  - *Providing a copy of each data item vs. providing a reference to each data item*?
  - *How to handle concurrency and insertion/deletion while iterator(s) are running*

Iterators (cont'd)

- Three primary methods of designing iterators

  1. *Pass a pointer to a function*
     - Not very OO...
     - Clumsy way to handle shared data...
  2. *Use in-class iterators* (a.k.a. *passive* or *internal* iterators)
     - Requires modification of class interface
     - Generally not reentrant...
  3. *Use out-of-class iterators* (a.k.a. *active* or *external* iterator)
     - Handles multiple simultaneously active iterators
     - May require special access to original class internals...
       * *i.e.*, use "friends"

Pointer to Function Iterator

- *e.g.*,

```
#include <stream.h>
template <class T>
class Vector {
public:
     /* Same as before */
     int apply (void (*ptf) (T &)) {
          for (int i = 0; i < this->size (); i++)
               (*ptf) (this->buf[i]);
     }
}
template <class T> void f (T &i) {
     cout << i << endl;
}
Vector<int> v (100);
// ...
v.apply (f);
```

In-class Iterator

- *e.g.*,

```
#include <stream.h>
template <class T>
class Vector {
public:
     // Same as before
     void reset (void) { this->i_ = 0; }
     bool advance (void) {
          return this->i_++ < this->size ();
     }
     T value (void) {
          return this->buf[this->i_ - 1];
     }
private:
     /* Same as before */
     size_t i_;
};
Vector<int> v (100);
// ...
for (v.reset (); v.advance () != false; )
     cout << "value = " << v.value () << "\n";
```

- Note, this approach is not re-entrant...

Out-of-class Iterator

- *e.g.*,

```
#include <stream.h>
#include "Vector.h"
template <class T>
class Vector_Iterator {
public:
     Vector_Iterator (const Vector<T> &v)
          : i_ (0), vr_ (v) {}
     bool advance (void) {
          return this->i_++ < this->vr_.size ();
     }
     T value (void) {
          return this->vr_[this->i_ - 1];
     }
private:
     Vector<T> &vr_;
     size_t i_;
};
Vector<int> v (100);
Vector_Iterator<int> iter (v);
while (iter.advance () != false)
     cout << "value = " << iter.value () << "\n";
```

- Note, this particular scheme does not require that Vector_Iterator be declared as a friend of class Vector
  - However, for efficiency reasons this is often necessary in more complex ADTs

Miscellaneous ADT Issues in C++

- References
- **const** methods
- **static** methods
- **static** data members
- **mutable** Type Qualifier
- Arrays of class objects

References

- Parameters, return values, and variables can all be defined as "references"
  - This is primarily done for efficiency

- *Call-by-reference* can be used to avoid the run-time impact of passing large arguments by value
  - Note, there is a trade-off between indirection vs copying

```
struct Huge { int size_; int array_[100000]; };
int total (const Huge &h) {
    int count = 0;
    for (int i = 0; i < h.size_; i++)
        count += h.array_[i];
    return count;
}

Huge h;

int main (void) {
    /* ...*/
    // Small parameter passing cost...
    int count = total (h);
}
```

References (cont'd)

- The following behaves like Pascal's VAR parameter passing mechanism (a.k.a. *call-by-reference*):

```
double square (double &x) { return x *= x; }
int bar (void) {
      double foo = 10.0;
      square (foo);
      cout << foo; // prints 100.0
}
```

- In C this would be written using explicit dereferencing:

```
double square (double *x) { return *x *= *x; }
int bar (void) {
      double foo = 10.0;
      square (&foo);
      printf ("%f", foo); /* prints 100.0 */
}
```

- Note, reference variables may lead to subtle aliasing problems when combined with side-effects:

```
cout << (square (foo) * foo);
// output result is not defined!
```

References (cont'd)

- A function can also return a reference to an object, *i.e.*, an *lvalue*
  - Avoids cost of returning by an object by value
  - Allows the function call to be an *lvalue*

    ```
    Employee &boss_of (const Employee &);
    Employee smith, jones, vacant;
    if (boss_of (smith) == jones)
         boss_of (smith) = vacant;
    ```

  - Note, this is often done with **operator**[], *e.g.*,

    ```
    Vector<int> v (10);
    v[3] = 100; // v.operator[] (3) = 100;
    int i = v[3]; // int i = v.operator[] (3);
    ```

References (cont'd)

- References are implemented similarly to **const** pointers. Conceptually, the differences between references and pointers are:
  - *Pointers are first class objects, references are not*
    - *e.g.*, you can have an array of pointers, but you can't have an array of references
  - References must refer to an actual object, but pointers can refer to lots of other things that aren't objects, *e.g.*,
    - Pointers can refer to the special value 0 in C++ (often referred to as NULL)
    - Also, pointers can legitimately refer to a location one past the end of an array

- In general, use of references is safer, less ambiguous, and much more restricted than pointers (this is both good and bad, of course)

Const Methods

- When a user-defined class object is declared as **const**, its methods cannot be called unless they are declared to be **const** methods
  - *i.e.*, a **const** method must *not* modify its member data directly

- This allows read-only user-defined objects to function correctly, *e.g.*,

```
class Point {
public:
    Point (int x, int y): x_ (x), y_ (y) {}
    int dist (void) const {
        return ::sqrt (this->x_ * this->x_
            + this->y_ * this->y_);
    }
    void move (int dx, int dy) {
        this->x_ += dx; this->y_ += dy;
    }
private:
    int x_, y_;
};
const Point p (10, 20);
int d = p.dist (); // OK
p.move (3, 5); // ERROR
```

Static Data Members

- A **static** data member has exactly one instantiation for the entire class (as opposed to one for each object in the class), *e.g.*,

```
class Foo {
public:
      int a_;
private:
      // Must be defined exactly once outside header!
      // (usually in corresponding .C file)
      static int s_;
};
Foo x, y, z;
```

- Note:
  - There are three distinct addresses for Foo::a (*i.e.*, &x.a_, &y.a_, &z.a_)
  - There is only *one* Foo::s, however...

- Also note:

```
&Foo::s_ == (int *);
&Foo::a_ == (int Foo::*); // pointer to data member
```

Static Methods

- A static method may be called on an object of a class, or on the class itself *without supplying an object* (unlike non-static methods...)

- Note, there is no **this** pointer in a static method

  – *i.e.*, a static method cannot access non-static class data and functions

```
class Foo {
public:
     static int get_s1 (void) {
          this->a_ = 10; /* ERROR! */
          return Foo::s_;
     }
     int get_s2 (void) {
          this->a_ = 10; /* OK */
          return Foo::s_;
     }
private:
     int a_;
     static int s_;
};
```

Static Methods (cont'd)

- The following calls are legal:

```
Foo f;
int i1, i2, i3, i4;
i1 = Foo::get_s1 ();
i2 = f.get_s2 ();
i3 = f.get_s1 ();
i4 = Foo::get_s2 (); // error
```

- Note:

```
&Foo::get_s1 == int (*)(void);

// pointer to method
&Foo::get_s2 == int (Foo::*)(void);
```

Mutable Type Qualifier

- The constness of an object's storage is determined by whether the object is constructed as **const**

- An attempt to modify the contents of **const** storage (via casting of pointers or other tricks) results in undefined behavior

  – It is possible (though not encouraged) to "cast-away" the **const**ness of an object. This is not guaranteed to be portable or correct, however!

    ```
    const int i = 10;
    //...
    * (int *) &i = 100; // Asking for trouble!
    ```

- If a data member is declared with the storage class **mutable**, then that member is modifiable even if the containing object is **const**

Mutable Type Qualifier (cont'd)

- *e.g.*,

```
class Foo {
public:
     Foo (int a, int b): i_ (a), j_ (b) {}
     mutable int i_;
     int j_;

};
const Foo bar;

// the following must be written in a context with
// access rights to Foo::i_ and Foo::j_.

bar.i_ = 5; // well formed and defined
bar.j_ = 5; // not well-formed
*(int *)(&bar.j_) = 5; // well-formed but undefined behavior
// better style, but still undefined behavior
if (int *i = const_cast<int *>(&bar.j_))
     i = 5;
```

Mutable Type Qualifier (cont'd)

- A consequence of **mutable** is that a object is ROMable if

  1. Its class doesn't have any mutable data members

  2. The compiler can figure out its contents after construction at compile time

  3. The compiler can cope with any side effects of the constructor and destructor

     – or can determine that there aren't any

Arrays of Objects

- In order to create an array of objects that have constructors, one constructor must take no arguments
  - Either directly or via default arguments for all formal parameters
  - *e.g.*,

    ```
    Vector<Vector<int> > vector_vector1;
    Vector<int> vector_vector2[100];
    Vector<int> *vector_vector_ptr = new Vector<int>[size];
    ```

- The constructor is called for each element

- If array created dynamically via **new**, then **delete** must use an empty []
  - This instructs the compiler to call the destructor the correct number of times, *e.g.*,

    ```
    delete [] vector_vector_ptr;
    ```

Anonymous Unions

- A **union** is a structure who member objects all begin at offset zero and whose size is sufficient to contain any of its member objects
  - They are often used to save space

- A union of the form **union** { *member-list* }; is called an anonymous union; it defines an unnamed object
  - The union fields are used directly without the usual member access syntax, *e.g.*,

```
void f (void) {
      union { int a_; char *p_; };
      a_ = 1; p_ = "Hello World\n";
      // a_ and p_ have the same address!
      // i.e., &a_ == &p_
}
```

Anonymous Unions (cont'd)

- Here's an example that illustrates a typical way of using unions, *e.g.*,

```
struct Types {
     enum Type {INT, DOUBLE, CHAR} type_;
     union { int i_; double d_; char c_; };
} t;
if (t.type_ == Types::DOUBLE) t.d_ = 100.02;

// Q: "what is the total size of struct Types?"
// Q: "What if union were changed to struct?"
```

- Note that C++ provides other language features that makes unions less necessary (compared to C)

  – *e.g.*, inheritance with dynamic binding

Anonymous Unions (cont'd)

- Some restrictions apply:
  - *Unions in general*
    - A union may not be used as a base class and can have no virtual functions
    - An object of a class with a constructor or destructor or a user-defined assignment operator cannot be a member of a union
    - A union can have no **static** data members
  - *Anonymous unions*
    - Global anonymous unions must be declared **static**
    - An anonymous union may *not* have **private** or **protected** members
    - An anonymous union may not have methods

Summary

- A major contribution of C++ is its support for defining abstract data types (ADTs), *e.g.*,
  - Classes
  - Parameterized types
  - Exception handling
- For many systems, successfully utilizing C++'s ADT support is more important than using the OO features of the language, *e.g.*,
  - Inheritance
  - Dynamic binding