C++ Support for Abstract Data Types

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Topics

- *Describing Objects Using ADTs*
- *Built-in vs. User-defined ADTs*
- *C++ Support*

Describing Objects Using ADTs

- An ADT is a collection of data and associated operations for manipulating that data
- ADTs support *abstraction*, *encapsulation*, and *information hiding*
- They provide equal attention to data *and* operations
- Common examples of ADTs:
  - *Built-in types*: boolean, integer, real, array
  - *User-defined types*: stack, queue, tree, list

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, destroy/dispose, push, pop`**, **`is_empty, is_full`**, *etc.*
- queue
  - *Values*: Queue elements, *i.e.*, queue of *X*. . .
  - *Operations*: **`create, destroy/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.*

C++ Support for ADTs

- *C++ Classes*
- *Automatic Initialization and Termination*
- *Friends*
- *Assignment and Initialization*
- *Overloading*
- *Parameterized Types*
- *Iterators*
- *Miscellaneous Issues*

C++ Classes

- 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)

- A `struct` is interpreted as a class with all data objects and methods declared in the public section
- By default, all class members are private and all struct members are public
- A class definition does *not* allocate storage for any objects
- Data members and member functions (i.e., methods)

C++ Class Components (cont'd)

- The *this* pointer
  - Used in the source code to refer to a pointer to the object on which the method is called
- *Friends*
  - Non-class functions granted privileges to access internal class information, typically for efficiency reasons

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) {}
  // . . .
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
- Base/member initialization section only applies to constructors

Base/Member Initialization Section

- Five 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
5. Initializing virtual base class(es), in most derived class (when they don't have default constructor(s))

- One optional case:

1. Initializing built-in data members

Base/Member Initialization Section (cont'd)

```
class Vector { public: Vector (size_t len); /* . . . */ };
class String { public: String (const char *str); /* . . .
class Stack : private Vector // Base class
{
public:
  Stack (size_t len, const 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
  // . . .
};
```

Base/Member Initialization Section (cont'd)

- References (and **consts**) *must* be initialized

```
class Vector_Iterator {
public:
  Vector_Iterator (const Vector &v): vr_ (v), i_ (0) {}
  // . . .
private:
  Vector &vr_; // reference
  size_t i_;
};
```

Friends

- A class may grant access to its private data and methods by including *friend* declarations in the class definition, *e.g.*,

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

- Function **product** can access **Vector**'s private parts:

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

Friends (cont'd)

- A class may confer friendship on *entire classes*, *selected methods in a particular class*, *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 friends weakens information hiding
  - In particular, it leads to tightly-coupled implementations that are overly reliant on certain *naming* and *implementation* details
- For this reason, friends are known as the 'goto of access protection mechanisms!'
- Note, C++ inline (accessor) functions reduce the need for friends . . .

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)

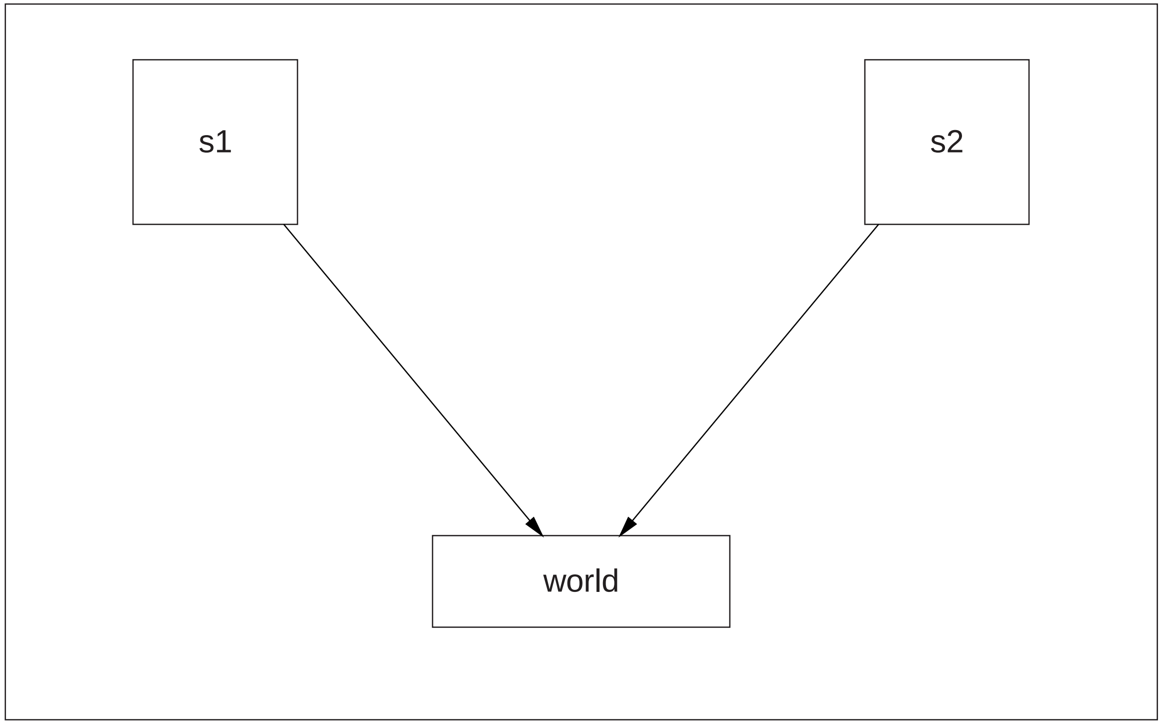
```
class String {
public:
  String (const char *t)
    : len_ (t == 0 ? 0 : strlen (t)) {
    if (this->len_ == 0)
      throw range_error ();
    this->str_ = strcpy (new char [len_ + 1], t);
  }
  ~String (void) { delete [] this->str_; }
// . . .
private:
  size_t len_;
  char *str_;
};
```

Assignment and Initialization (cont'd)

```
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"
Vector<int> bar (Vector<int>);

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

  Vector<int> v2 = v1; // Initialize new v2 from v1
                       // Same net effect 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 handled using the initialization semantics of the *copy constructor*

Assignment and Initialization (cont'd)

- Assignment is different than initialization because the left hand object already exists for assignment
- Therefore, C++ provides two 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];
}
```

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)

- 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 =

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
```

Restricting Assignment and Initialization (cont'd)

- A similar idiom 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 the object, **`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 . . .

```
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 sequence (comma) **`operator ,`**
  - the ternary **`operator ? :`**
  - the auto-increment **`operator ++`**
- You may not overload:
  - the scope resolution **`operator ::`**
  - the member selection (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:

```
int divide (double, double);
double divide (double, double);
```

Overloading (cont'd)

- **`const`** and **`non-const`** functions are different functions, so const-ness may be used to distinguish return values, *e.g.*,

```
char &operator[] (unsigned int);
const char &operator[] (unsigned int) const;
```

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+ (const String&, const char *);
  friend String operator+ (const String&,const String&);
  friend String operator+ (const char *, const String&);
  friend ostream &operator<< (ostream &, const String &);
};
```

Overloading (cont'd)

```
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)

- 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
- 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 . . .
```

Overloading (cont'd)

- 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)

- So, do not use operator overloading unless necessary!
- Instead, many operations may be written using functions with explicit arguments, *e.g.*,

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

- or define and use the short-hand operator *x*= instead, *e.g.*, **a = b + c * d;** can be represented by:

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

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 (or non-template methods)
- ANSI/ISO C++ allows a programmer to explicitly instantiate parameterized types, *e.g.*, **`template class Vector<int>;`**

Parameterized Types (cont'd)

- C++ templates may also be used to parameterize functions. The compiler generates all the necessary code!

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

int main (int, char *[]) {
  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);
  return 0;
}
```

Parameterized Types (cont'd)

- C++ standard library provides standard containers, algorithms iterators and functors. The library is generic in the sense that they are heavily parameterized.
  - Containers - e.x, vectors, list, map, queue etc.
  - Algorithm - e.x, copy, sort, find, count etc.
  - Iterators - e.x, Input, Output, Forward, BiDirectional, Random Access and Trivial
  - Function Objects or Functors - e.x, plus, minus, multiplies etc.
- They were called STL in earlier versions of C++

Template Metaprograms

- Make the compiler act as an interpreter.
- Made possible by C++ template features.
- These programs need not be executed. They generate their output at compile time.

```
template<int N> class Power2 {
public:
    enum { value = 2 * Power2<N-1>::value };
};
class Power2<1> {
public:
    enum { value = 2 };
};
```

Template Metaprograms (cont'd)

- Very powerful when combined with normal C++ code.
- A hybrid approach would result in faster code.
- Template metaprograms can be written for specific algorithms and embedded in code.
- Generates useful code for specific input sizes during compile times.
- Basically, it is an extremely early binding mechanism as opposed to traditional late binding used with C++.
- Can torture your compiler, and not many compilers can handle this.

Template Metaprograms (cont'd)

- A simple do while loop

```
template<int I>
class loop {
private:  enum { go = (I-1) != 0 };
public:   static inline void f() {
         // Whatever needs to go here
         loop<go ? (I-1) : 0>::f(); }
};
class loop<0> {
public:
    static inline void f()
    { }
};
loop<N>::f();
```

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)

- Iterators are central to generic programming

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 **`friend`**s

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 **`friend`**s

Pointer to Function Iterator Example

```
#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 Example

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

Out-of-class Iterator Example

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

Out-of-class Iterator Example (cont'd)

- 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++

- const methods
- New (ANSI) casts
- References
- static methods
- static data members

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, or indirectly by calling non-const methods

Const Methods (cont'd)

- 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
```

New (ANSI) casts

- **static_cast** performs a standard, nonpolymorphic cast
  - `unsigned int invalid = static_cast<unsigned int> (-1);`
- **const_cast** removes const-ness

```
void Foo::func (void) const
{
  // Call a non-const member function from a
  // const member function.  Often dangerous!!!!
  const_cast<Foo *> (this)->func2 ();
}
```

New (ANSI) casts, (cont'd)

- **`reinterpret_cast`** converts types, possibly in an implementation-dependent manner
  - `long random = reinterpret_cast<long> (&func);`
- **`dynamic_cast`** casts at run-time, using RTTI

```
void func (Base *bp) {
  Derived *dp = dynamic_cast<Derived *> (bp);
  if (dp)
    // bp is a pointer to a Derived object
}
```

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

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)

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;
```

Static Data Members (cont'd)

- Note:
  - There are three distinct addresses for **Foo::a**, *i.e.*, **&x.a_, &y.a_, &z.**
  - 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

Static Methods (cont'd)

- *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)

- Most of 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 (*)();

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

Summary

- A major contribution of C++ is its support for defining abstract data types (ADTs), *e.g.*,
  - Classes
  - Parameterized types
- 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