The C++ Programming Language

Single and Multiple Inheritance in C++

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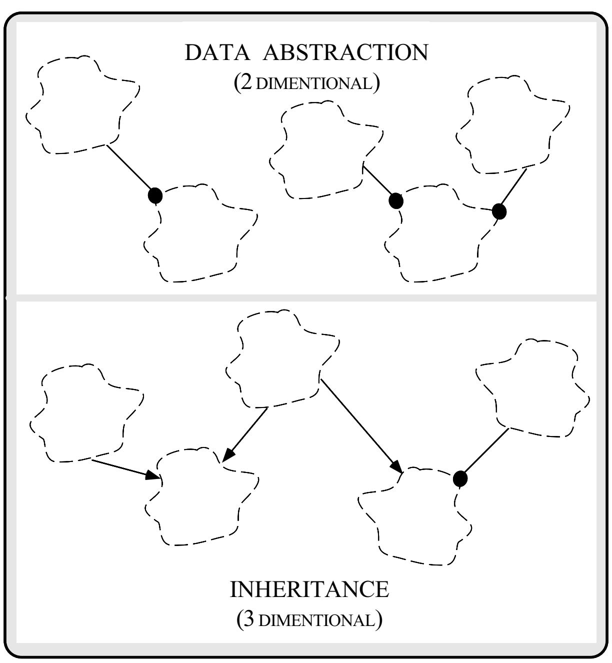
Background

- Object-oriented programming is often defined as the combination of *Abstract Data Types* (ADTs) with *Inheritance* and *Dynamic Binding*

- Each concept addresses a different aspect of system decomposition:

  1. ADTs decompose systems into *two-dimensional* grids of modules
     – Each module has *public* and *private* interfaces
  2. Inheritance decomposes systems into *three-dimensional* hierarchies of modules
     – Inheritance relationships form a "lattice"
  3. Dynamic binding enhances inheritance
     – *e.g.*, defer implementation decisions until late in the design phase or even until run-time!

Data Abstraction vs. Inheritance



Motivation for Inheritance

- Inheritance allows you to write code to handle certain cases and allows other developers to write code that handles more specialized cases, while your code continues to work

- Inheritance partitions a system architecture into semi-disjoint components that are related hierarchically

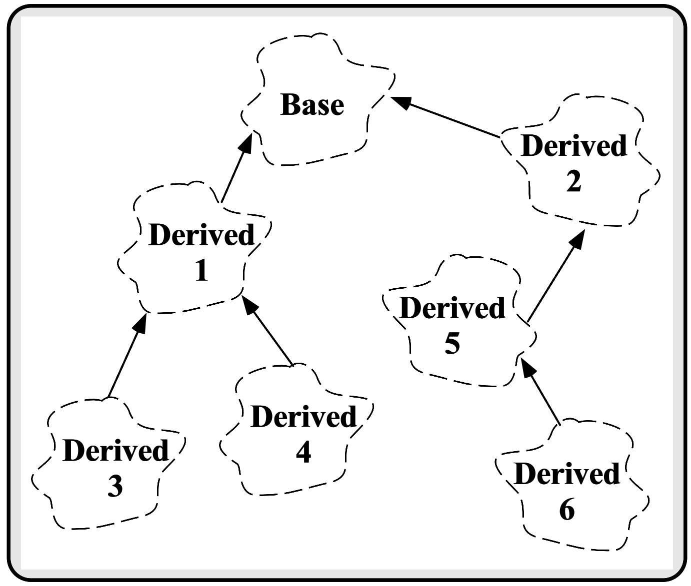
- Therefore, we may be able to modify and/or reuse sections of the inheritance hierarchy without disturbing existing code, *e.g.*,
  – Change sibling subtree interfaces
    ∗ *i.e.*, a consequence of inheritance
  – Change implementation of ancestors
    ∗ *i.e.*, a consequence of data abstraction

Inheritance Overview

- A type (called a *subclass* or *derived* type) can inherit the characteristics of another type(s) (called a *superclass* or *base type*)
  - The term *subclass* is equivalent to *derived type*

- A derived type acts just like the base type, except for an explicit list of:
  1. *Specializations*
     - Change implementations *without* changing the base class interface
       * Most useful when combined with dynamic binding
  2. *Generalizations/Extensions*
     - Add new operations or data to derived classes

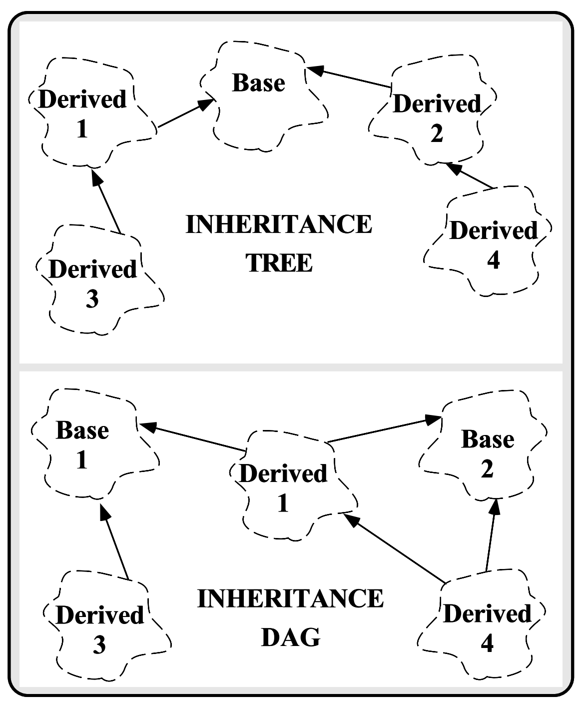
Visualizing Inheritance



Types of Inheritance

- Inheritance comes in two forms, depending on number of *parents* a subclass has
  1. *Single Inheritance* (SI)
     - Only one parent per derived class
     - Form an inheritance "tree"
     - SI requires a small amount of run-time overhead when used with dynamic binding
     - *e.g.*, Smalltalk, Simula, Object Pascal
  2. *Multiple Inheritance* (MI)
     - More than one parent per derived class
     - Forms an inheritance "Directed Acyclic Graph" (DAG)
     - Compared with SI, MI adds additional run-time overhead (also involving dynamic binding)
     - *e.g.*, C++, Eiffel, Flavors (a LISP dialect)

Inheritance Trees vs. Inheritance DAGs



Inheritance Benefits

1. *Increase reuse and software quality*
   - Programmers reuse the base classes instead of writing new classes
     - Integrates *black-box* and *white-box* reuse by allowing extensibility and modification without changing existing code
   - Using well-tested base classes helps reduce bugs in applications that use them
   - Reduce object code size
2. *Enhance extensibility and comprehensibility*
   - Helps support more flexible and extensible architectures (along with dynamic binding)
     - *i.e.*, supports the open/closed principle
   - Often useful for modeling and classifying hierarchically-related domains

Inheritance Liabilities

1. May create deep and/or wide hierarchies that are difficult to understand and navigate without class browser tools
2. May decrease performance slightly
   - *i.e.*, when combined with *multiple inheritance* and *dynamic binding*
3. Without dynamic binding, inheritance has only limited utility
   - Likewise, dynamic binding is almost totally useless without inheritance
4. Brittle hierarchies, which may impose dependencies upon ancestor names

Inheritance in C++

- Deriving a class involves an extension to the C++ class declaration syntax
- The class head is modified to allow a *derivation list* consisting of base classes
- *e.g.*,

```
class Foo { /* ...};
class Bar : public Foo { /* ...};
class Foo : public Foo, public Bar { /* ...};
```


Key Properties of C++ Inheritance

- The base/derived class relationship is explicitly recognized in C++ by predefined standard conversions
  - *i.e.*, a pointer to a derived class may always be assigned to a pointer to a base class that was inherited *publically*
    - But not vice versa...
- When combined with dynamic binding, this special relationship between inherited class types promotes a type-secure, *polymorphic* style of programming
  - *i.e.*, the programmer need not know the actual type of a class at compile-time
  - Note, C++ is not truly polymorphic
    - *i.e.*, operations are not applicable to objects that don't contain definitions of these operations at some point in their inheritance hierarchy

Simple Screen Class

- The following code is used as the base class:

```
class Screen {
public:
    Screen (int = 8, int = 40, char = ' ');
    ~Screen (void);
    short height (void) const { return this->height_; }
    short width (void) const { return this->width_; }
    void height (short h) { this->height_ = h; }
    void width (short w) { this->width_ = w; }
    Screen &forward (void);
    Screen &up (void);
    Screen &down (void);
    Screen &home (void);
    Screen &bottom (void);
    Screen &display (void);
    Screen &copy (const Screen &);
    // ...
private:
    short height_, width_;
    char *screen_, *cur_pos_;
};
```


Subclassing from Screen

- `class Screen` can be a public base class of `class Window`

- *e.g.*,

```
class Window : public Screen {
public:
    Window (const Point &, int rows = 24,
        int columns = 80,
        char default_char = ' ');
    void set_foreground_color (Color &);
    void set_background_color (Color &);
    void resize (int height, int width);
    // ...
private:
    Point center_;
    Color foreground_;
    Color background_;
    // ...
};
```

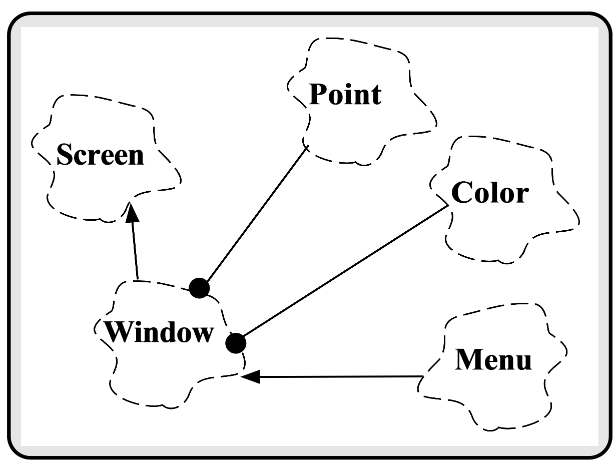

Multiple Levels of Derivation

- A derived class can itself form the basis for further derivation, *e.g.*,

```
class Menu : public Window {
public:
    void set_label (const char *l);
    Menu (const Point &, int rows = 24,
        int columns = 80,
        char default_char = ' ');
    // ...
private:
    char *label_;
    // ...
};
```

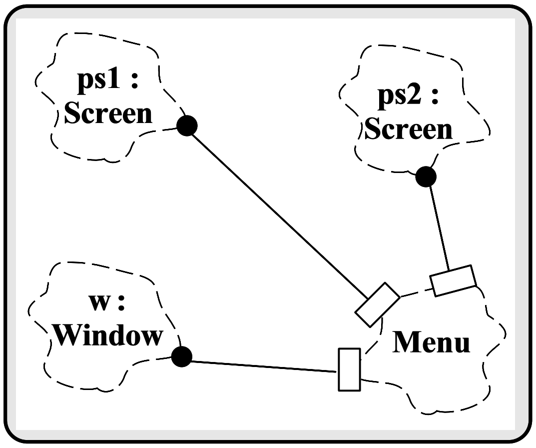
- `class Menu` inherits data and methods from both `Window` and `Screen`
  - *i.e.*, **sizeof** (Menu) >= **sizeof** (Window) >= **sizeof** (Screen)

The Screen Inheritance Hierarchy



- Screen/Window/Menu hierarchy

Variations on a Screen...



- A pointer to a derived class can be assigned to a pointer to any of its *public* base classes without requiring an explicit cast:

```
Menu m; Window &w = m; Screen *ps1 = &w;
Screen *ps2 = &m;
```


Using the Screen Hierarchy

- *e.g.*,

```
class Screen { public: virtual void dump (ostream &); = 0 }
class Window : public Screen {
      public: virtual void dump (ostream &);
};
class Menu : public Window {
      public: virtual void dump (ostream &);
};
// stand-alone function
void dump_image (Screen *s, ostream &o) {
      // Some processing omitted
      s->dump (o);
      // (*s->vptr[1]) (s, o));
}

Screen s; Window w; Menu m;
Bit_Vector bv;

// OK: Window is a kind of Screen
dump_image (&w, cout);
// OK: Menu is a kind of Screen
dump_image (&m, cout);
// OK: argument types match exactly
dump_image (&s, cout);
// Error: Bit_Vector is not a kind of Screen!
dump_image (&bv, cout);
```


Using Inheritance for Specialization

- A derived class *specializes* a base class by adding new, more specific *state variables* and *methods*
  - Method use the same interface, even though they are implemented differently
    - *i.e.*, "overridden"
  - Note, there is an important distinction between *overriding*, *hiding*, and *overloading*...
- A variant of this is used in the *template method* pattern
  - *i.e.*, behavior of the base class relies on functionality supplied by the derived class
  - This is directly supported in C++ via *abstract base classes* and *pure virtual functions*

Specialization Example

- Inheritance may be used to obtain the features of one data type in another closely related data type
- For example, class Date represents an arbitrary Date:

```
class Date {
public:
      Date (int m, int d, int y);
      virtual void print (ostream &s) const;
      // ...
private:
      int month_, day_, year_;
};
```

- Class Birthday derives from Date, adding a name field representing the person's birthday, *e.g.*,

```
class Birthday : public Date {
public:
      Birthday (const char *n, int m, int d, int y)
            : Date (m, d, y), person_ (strdup (n)) {}
      ~Birthday (void) { free (person_); }
      virtual void print (ostream &s) const;
      // ...
private:
      const char *person_;
};
```

Implementation and Use-case

- Birthday::print could print the person's name as well as the date, *e.g.*,

```
void Birthday::print (ostream &s) const {
      s << this->person_ << " was born on ";
      Date::print (s);
      s << "\n";
}
```

- *e.g.*,

```
const Date july_4th (7, 4, 1993);
Birthday my_birthday ("Douglas C. Schmidt", 7, 18, 1962);

july_4th.print (cerr);
// july 4th, 1993
my_birthday.print (cout);
// Douglas C. Schmidt was born on july 18th, 1962

Date *dp = &my_birthday;
dp->print (cerr);
// ??? what gets printed ???
// (*dp->vptr[1])(dp, cerr);
```


Alternatives to Specialization

- Note that we could also use *object composition* instead of *inheritance* for this example, *e.g.*,

```
class Birthday {
public
      Birthday (char *n, int m, int d, int y):
            date_ (m, d, y), person_ (n) {}
      // same as before
private:
      Date date_;
      char *person_;
};
```

- However, in this case we would not be able to utilize the dynamic binding facilities for base classes and derived classes
  - *e.g.*,

    ```
    Date *dp = &my_birthday;
    // ERROR, Birthday is not a subclass of date!
    ```

  - While this does not necessarily affect reusability, it does affect extensibility...

Using Inheritance for Extension/Generalization

- Derived classes add *state variables* and/or *operations* to the *properties* and *operations* associated with the base class
  - Note, the interface is generally widened!
  - Data member and method access privileges may also be modified
- Extension/generalization is often used to faciliate reuse of *implementations*, rather than *interface*
  - However, it is not always necessary or correct to export interfaces from a base class to derived classes

Extension/Generalization Example

- Using `class Vector` as a private base class for derived `class Stack`

```
class Stack : private Vector { /* ...*/ };
```

- In this case, Vector's `operator[]` may be reused as an implementation for the Stack `push` and `pop` methods
  - Note that using private inheritance ensures that `operator[]` does not show up in the interface for class Stack!
- Often, a better approach in this case is to use a composition/Has-A rather than a descendant/Is-A relationship...

Vector Interface

- Using `class Vector` as a base class for a derived class such as class `Checked_Vector` or class `Ada_Vector`
  - One can define a Vector class that implements an unchecked, uninitialized array of elements of type T

- *e.g.*, /* File Vector.h (incomplete wrt initialization and assignment) */

```
// Bare-bones implementation, fast but not safe
template <class T>
class Vector {
public:
    Vector (size_t s);
    ~Vector (void);
    size_t size (void) const;
    T &operator[] (size_t index);

private:
    T *buf_;
    size_t size_;
};
```


Vector Implementation

- *e.g.*,

```
template <class T>
Vector<T>::Vector (size_t s): size_ (s), buf_ (new T[s]) {}

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

template <class T> size_t
Vector<T>::size (void) const { return this->size_; }

template <class T> T &
Vector<T>::operator[] (size_t i) { return this->buf_[i]; }

int main (void) {
    Vector<int> v (10);
    v[6] = v[5] + 4; // oops, no initial values
    int i = v[v.size ()]; // oops, out of range!
    // destructor automatically called
}
```


Benefits of Inheritance

- Inheritance enables modification and/or extension of ADTs *without changing the original source code*
  - *e.g.*, someone may want a variation on the basic Vector abstraction:
    1. A vector whose bounds are checked on every reference
    2. Allow vectors to have lower bounds other than 0
    3. Other vector variants are possible too...
       * *e.g.*, automatically-resizing vectors, initialized vectors, etc.

- This is done by defining new derived classes that inherit the characteristics of the `Vector` base class
  - Note that inheritance also allows code to be shared

Checked_Vector Interface

- The following is a subclass of Vector that allows run-time range checking:

- /* File Checked-Vector.h (incomplete wrt initialization and assignment) */

```
struct RANGE_ERROR {
    "range_error" (size_t index);
    // ...

};
template <class T>
class Checked_Vector : public Vector<T> {
public:
    Checked_Vector (size_t s);
    T &operator[] (size_t i) throw (RANGE_ERROR);
    // Vector::size () inherited from base class Vector.
protected:
    bool in_range (size_t i) const;
private:
    typedef Vector<T> inherited;
};
```

Implementation of Checked_Vector

- *e.g.*,

```
template <class T> bool
Checked_Vector<T>::in_range (size_t i) const {
    return i < this->size ();
}

template <class T>
Checked_Vector<T>::Checked_Vector (size_t s)
    : inherited (s) {}

template <class T> T &
Checked_Vector<T>::operator[] (size_t i)
    throw (RANGE_ERROR)
{
    if (this->in_range (i))
        return (*(inherited *) this)[i];
        // return BASE::operator[](i);
    else
        throw RANGE_ERROR (i);
}
```


Checked_Vector Use-case

- *e.g.*,

```
#include "Checked_Vector.h"

typedef Checked_Vector<int> CV_INT;

int foo (int size)
{
    try
    {
        CV_INT cv (size);
        int i = cv[cv.size ()]; // Error detected!
                    // exception raised...
        // Call base class destructor
    }
    catch (RANGE_ERROR)
    { /* ...*/ }
}
```


Design Tip

- Note, dealing with parent and base classes
  - It is often useful to write derived classes that do not encode the names of their direct parent class or base class in any of the method bodies
  - Here's one way to do this systematically:

```
class Base {
public:
    int foo (void);
};
class Derived_1 : public Base {
    typedef Base inherited;
public:
    int foo (void) { inherited::foo (); }
};
class Derived_2 : public Derived_1 {
    typedef Derived_1 inherited;
public:
    int foo (void) {
        inherited::foo ();
    }
};
```

  - This scheme obviously doesn't work as transparently for multiple inheritance...

Ada_Vector Interface

- The following is an Ada Vector example, where we can have array bounds start at something other than zero

- /* File ada_vector.h (still incomplete *wrt* initialization and assignment....) */

```
#include "vector.h"
// Ada Vectors are also range checked!
template <class T>
class Ada_Vector : private Checked_Vector<T> {
public:
    Ada_Vector (size_t l, size_t h);
    T &operator ()(size_t i) throw (RANGE_ERROR)
    inherited::size; // explicitly extend visibility
private:
    typedef Checked_Vector<T> inherited;
    size_t lo_bnd_;
};
```

Ada_Vector Implementation

- *e.g.*, class Ada_Vector (cont'd)

```
template <class T>
Ada_Vector<T>::Ada_Vector (size_t lo, size_t hi)
    : inherited (hi − lo + 1), lo_bnd_ (lo) {}

template <class T> T &
Ada_Vector<T>::operator ()(size_t i)
    throw (RANGE_ERROR) {
    if (this->in_range (i − this->lo_bnd_))
        return Vector<T>::operator[] (i − this->lo_bnd_);
        // or Vector<T> &self = *(Vector<T> *) this;
        // self[i − this->lo_bnd_];
    else
        throw RANGE_ERROR (i);
}
```


Ada_Vector Use-case

- Example Ada Vector Usage (File main.C)

```
#include <iostream.h>
#include <stdlib.h>
#include "ada_vector.h"

int main (int argc, char *argv[]) {
    try {
        size_t lower = ::atoi (argv[1]);
        size_t upper = ::atoi (argv[2]);
        Ada_Vector<int> ada_vec (lower, upper);

        ada_vec (lower) = 0;

        for (size_t i = lower + 1; i <= ada_vec.size (); i++)
            ada_vec (i) = ada_vec (i − 1) + 1;

        // Run-time error, index out of range
        ada_vec (upper + 1) = 100;

        // Vector destructor called when
        // ada_vec goes out of scope
    }
    catch (RANGE_ERROR) { /* ...*/ }
}
```


Memory Layout

- Memory layouts in derived classes are created by concatenating memory from the base class(es)
  - *e.g.*, // from the cfront-generated .c file

```
struct Vector {
    T *buf__6Vector;
    size_t size__6Vector;
};
struct Checked_Vector {
    T *buf__6Vector;
    size_t size__6Vector;
};
struct Ada_Vector {
    T *buf__6Vector; // Vector
    size_t size__6Vector; // part
    size_t lo_bnd__10Ada_Vector; // Ada_Vector
};
```

- The derived class constructor calls the base constructor in the "base initialization section," *i.e.*,

```
Ada_Vector<T>::Ada_Vector (size_t lo, size_t hi)
    : inherited (hi − lo + 1), lo_bnd_ (lo) {}
```


Base Class Constructor

- Constructors are called from the "bottom up"
- Destructors are called from the "top down"
- *e.g.*,

```
/* Vector constructor */
struct Vector *
__ct__6VectorFi (struct Vector *__0this, size_t __0s) {
    if (__0this || (__0this =
            __nw__FUi (sizeof (struct Vector))))
            ((__0this->size__6Vector = __0s),
            (__0this->buf__6Vector =
                __nw__FUi ((sizeof (int)) * __0s)));
    return __0this;
}
```

Derived Class Constructors

- *e.g.*,

```
/* Checked_Vector constructor */
struct Checked_Vector *__ct__14Checked_VectorFi (
      struct Checked_Vector *__0this, size_t __0s) {
      if (__0this || (__0this =
            __nw__FUi (sizeof (struct Checked_Vector))))
            __0this = __ct__6VectorFi (__0this, __0s);
      return __0this;
}
/* Ada_Vector constructor */
struct Ada_Vector *__ct__10Ada_VectorFiT1 (
      struct Ada_Vector *__0this, size_t __0lo, size_t __0hi) {
      if (__0this || (__0this =
            __nw__FUi (sizeof (struct Ada_Vector))))
            if (((__0this = __ct__14Checked_VectorFi (__0this,
                  __0hi − __0lo + 1))))
                  __0this->lo_bnd__10Ada_Vector = __0lo;
      return __0this;
}
```


Destructor

- Note, destructors, constructors, and assignment operators are *not* inherited

- However, they may be called automatically were necessary, *e.g.*,

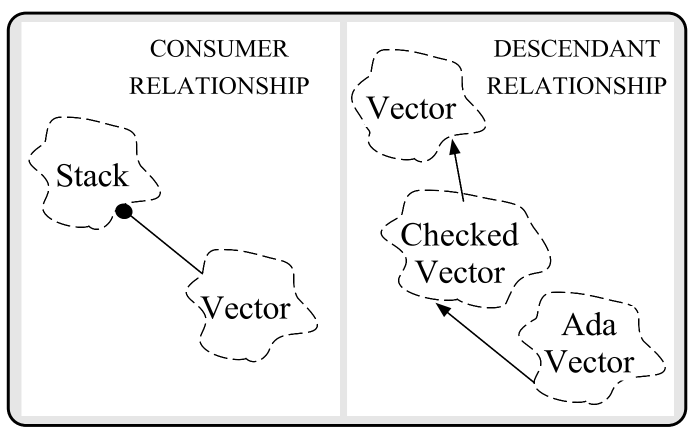
```
char __dt__6VectorFv (
      struct Vector *__0this, int __0__free) {
      if (__0this) {
            __dl__FPv ((char *) __0this->buf__6Vector);
            if (__0this)
                  if (__0__free & 1)
                        __dl__FPv ((char *) __0this);
      }
}
```


Describing Relationships Between Classes

- *Consumer/Composition/Aggregation*
  - A class is a consumer of another class when it makes use of the other class's services, as defined in its interface
    - ∗ For example, a Stack implementation could rely on an array for its implementation and thus be a consumer of the Array class
  - Consumers are used to describe a *Has-A* relationship

- *Descendant/Inheritance/Specialization*
  - A class is a descendant of one or more other classes when it is designed as an extension or specialization of these classes. This is the notion of inheritance
  - Descendants are used to describe an *Is-A* relationship

Has-A vs. Is-A Relationships



Interface vs. Implementation Inheritance

- Class inheritance can be used in two primary ways:

  1. *Interface inheritance*: a method of creating a subtype of an existing class for purposes of setting up dynamic binding, *e.g.*,
     - Circle is a subclass of Shape (*i.e.*, *Is-A* relation)
     - A Birthday is a subclass of Date
  2. *Implementation inheritance*: a method of reusing an implementation to create a new class type
     - *e.g.*, a **class** Stack that inherits from **class** Vector. A Stack is not really a subtype or specialization of Vector
     - In this case, inheritance makes implementation easier, since there is no need to rewrite and debug existing code.
       * This is called "using inheritance for reuse"
       * *i.e.*, a pseudo-*Has-A* relation

The Dangers of Implementation Inheritance

- Using inheritance for reuse may sometimes be a dangerous misuse of the technique
  - Operations that are valid for the base type may not apply to the derived type at all
    * *e.g.*, performing an subscript operation on a stack is a meaningless and potentially harmful operation

```
class Stack : public Vector {
    // ...
};
Stack s;
s[10] = 20; // could be big trouble!
```

  - In C++, the use of a **private** base class minimizes the dangers
    * *i.e.*, if a class is derived "private," it is illegal to assign the address of a derived object to a pointer to a base object
  - On the other hand, a consumer/Has-A relation might be more appropriate...

Private vs Public vs Protected Derivation

- Access control specifiers (*i.e.*, **public**, **private**, **protected**) are also meaningful in the context of inheritance
- In the following examples:
  - <....> represents actual (omitted) code
  - [....] is implicit
- Note, all the examples work for both data members and methods

Public Derivation

- *e.g.*,

```
class A {
public:
    <public A>
protected:
    <protected A>
private:
    <private A>
};

class B : public A {
public:
    [public A]
    <public B>
protected:
    [protected A]
    <protected B>
private:
    <private B>
};
```

Private Derivation

- *e.g.*,

```
class A {
public:
    <public A>
private:
    <private A>
protected:
    <protected A>
};

class B : private A { // also class B : A
public:
    <public B>
protected:
    <protected B>
private:
    [public A]
    [protected A]
    <private B>
};
```


Protected Derivation

- *e.g.*,

```
class A {
public:
    <public A>
protected:
    <protected A>
private:
    <private A>
};

class B : protected A {
public:
    <public B>
protected:
    [protected A]
    [public A]
    <protected B>
private:
    <private B>
};
```


Summary of Access Rights

- The following table describes the access rights of inherited methods
  - The vertical axis represents the access rights of the methods of base class
  - The horizontal access represents the mode of inheritance

```
                    INHERITANCE
                      ACCESS
    +-----------+-----+-----+-----+
M A | public    | pub | pro | pri |
E C +-----------+-----+-----+-----+
M C | protected | pro | pro | pri |
B E +-----------+-----+-----+-----+
E S | private   | n/a | n/a | n/a |
R S +-----------+-----+-----+-----+
                  p     p     p
                  u     r     r
                  b     o     i
                  l     t     v
```

- Note that the resulting access is always the most restrictive of the two

Other Uses of Access Control Specifiers

- Selectively redefine visibility of individual methods from base classes that are derived *privately*

```
class A {
public:
    int f ();
    int g_;
    ...
private:
    int p_;
};

class B : private A {
public:
    A::f; // Make public
protected:
    A::g_; // Make protected
};
```

Common Errors with Access Control Specifiers

- It is an error to "increase" the access of an inherited method in a derived class
  - *e.g.*, you may not say:

```
class B : private A {
// nor protected nor public!
public:
    A::p_; // ERROR!
};
```

- It is also an error to derive *publically* and then try to selectively decrease the visibility of base class methods in the derived class
  - *e.g.*, you may not say:

```
class B : public A {
private:
    A::f; // ERROR!
};
```


General Rules for Access Control Specifiers

- Private methods of the base class are not accessible to a derived class (unless the derived class is a **friend** of the base class)
- If the subclass is derived *publically* then:
  1. Public methods of the base class are accessible to the derived class
  2. Protected methods of the base class are accessible to derived classes and friends only

Caveats

- Using protected methods weakens the data hiding mechanism since changes to the base class implementation might affect all derived classes. *e.g.*,

```
class Vector {
public:
    //...
protected:
// allow derived classes direct access
    T *buf_;
    size_t size_;
};
class Ada_Vector : public Vector {
public:
    T &operator[] (size_t i) {
        return this->buf_[i];
    }
    // Note the strong dependency on the name buf_
};
```

- However, performance and design reasons may dictate use of the protected access control specifier
  - Note, inline functions often reduces the need for these efficiency hacks...

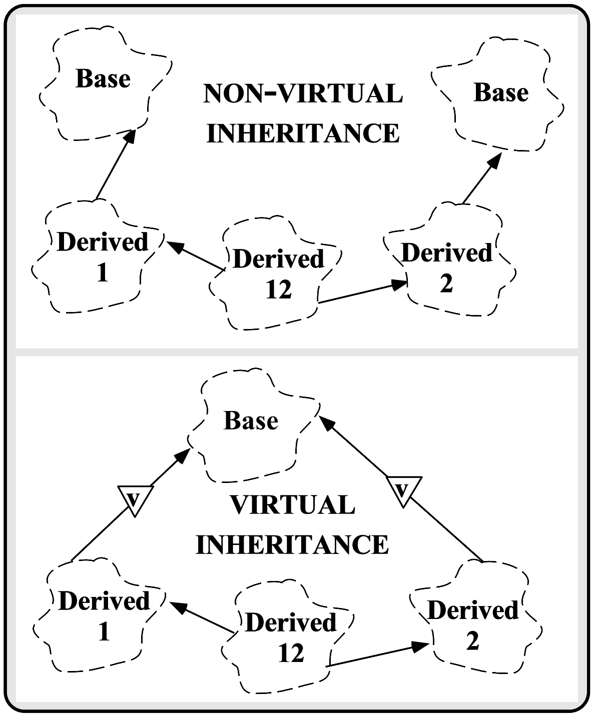
Overview of Multiple Inheritance in C++

- C++ allows *multiple inheritance*
  - *i.e.*, a class can be simultaneously derived from two or more base classes
  - *e.g.*,

```
class X { /* .... */ };
class Y : public X { /* .... */ };
class Z : public X { /* .... */ };
class YZ : public Y, public Z { /* .... */ };
```

  - Derived classes Y, Z, and YZ inherit the data members and methods from their respective base classes

Multiple Inheritance Illustrated



Liabilities of Multiple Inheritance

- A base class may legally appear only once in a derivation list, *e.g.*,
  - **class** Two_Vector : **public** Vector, **public** Vector // ERROR!
- However, a base class may appear multiple times within a derivation hierarchy
  - *e.g.*, `class YZ` contains two instances of `class X`
- This leads to two problems with multiple inheritance:
  1. It gives rise to a form of method and data member ambiguity
     - Explicitly qualified names and additional methods are used to resolve this
  2. It also may cause unnecessary duplication of storage
     - "Virtual base classes" are used to resolve this

Motivation for Virtual Base Classes

- Consider a user who wants an `Init_Checked_Vector`:

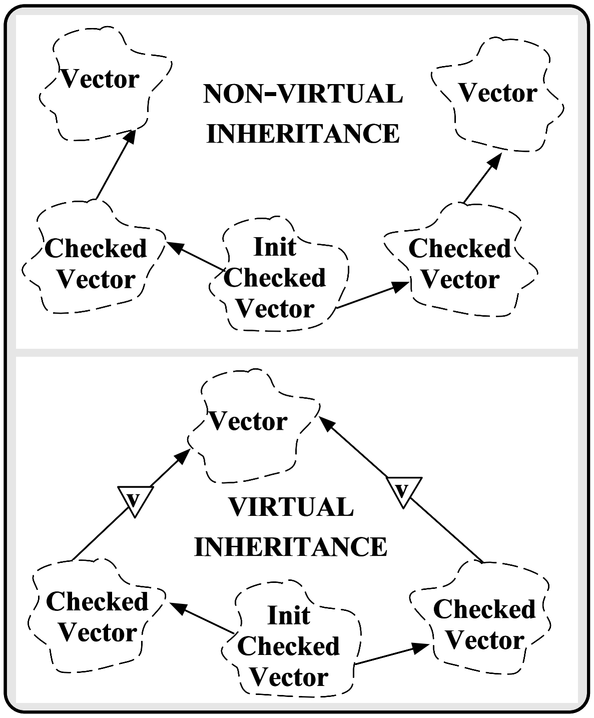
```
class Checked_Vector : public virtual Vector
{ /* .... */ };
class Init_Vector : public virtual Vector
{ /* .... */ };
class Init_Checked_Vector :
      public Checked_Vector, public Init_Vector
{ /* .... */ };
```

- In this example, the **virtual** keyword, when applied to a base class, causes `Init_Checked_Vector` to get one `Vector` base class instead of two

Overview of Virtual Base Classes

- Virtual base classes allow class designers to specify that a base class will be shared among derived classes
  - No matter how often a virtual base class may occur in a derivation hierarchy, only "one" shared instance is generated when an object is instantiated
    - ∗ Under the hood, pointers are used in derived classes that contain virtual base classes
- Understanding and using virtual base classes correctly is a non-trivial task since you must plan in advance
  - Also, you must be aware when initializing subclasses objects...
- However, virtual base classes are used to implement the client and server side of many implementations of CORBA distributed objects

Virtual Base Classes Illustrated



Initializing Virtual Base Classes

- With C++ you must chose one of two methods to make constructors work correctly for virtual base classes:

  1. You need to either supply a constructor in a virtual base class that takes no arguments (or has default arguments), *e.g.*,

     Vector::Vector (size_t size = 100); // has problems...

  2. Or, you must make sure the *most derived class* calls the constructor for the virtual base class in its *base initialization section*, *e.g.*,

```
Init_Checked_Vector (size_t size, const T &init):
    Vector (size), Check_Vector (size),
    Init_Vector (size, init)
```


Vector Interface Revised

- The following example illustrates templates, multiple inheritance, and virtual base classes in C++

```
#include <iostream.h>
#include <assert.h>
// A simple-minded Vector base class,
// no range checking, no initialization.
template <class T>
class Vector
{
public:
    Vector (size_t s): size_ (s), buf_ (new T[s]) {}
    T &operator[] (size_t i) { return this->buf_[i]; }
    size_t size (void) const { return this->size_; }
private:
    size_t size_;
    T *buf_;
};
```


Init_Vector Interface

- A simple extension to the Vector base class, that enables automagical vector initialization

```
template <class T>
class Init_Vector : public virtual Vector<T>
{
public:
    Init_Vector (size_t size, const T &init)
        : Vector<T> (size)
    {
        for (size_t i = 0; i < this->size (); i++)
            (*this)[i] = init;
    }
    // Inherits subscripting operator and size().
};
```

Checked_Vector Interface

- A simple extension to the Vector base class that provides range checked subscripting

```
template <class T>
class Checked_Vector : public virtual Vector<T>
{
public:
    Checked_Vector (size_t size): Vector<T> (size) {}
    T &operator[] (size_t i) throw (RANGE_ERROR) {
        if (this->in_range (i))
            return (*(inherited *) this)[i];
        else throw RANGE_ERROR (i);
    }
    // Inherits inherited::size.
private:
    typedef Vector<T> inherited;

    bool in_range (size_t i) const {
        return i < this->size ();
    }
};
```


Init_Checked_Vector Interface and Driver

- A simple multiple inheritance example that provides for both an initialized *and* range checked Vector

```
template <class T>
class Init_Checked_Vector :
    public Checked_Vector<T>, public Init_Vector<T> {
public:
    Init_Checked_Vector (size_t size, const T &init):
        Vector<T> (size),
        Init_Vector<T> (size, init),
        Checked_Vector<T> (size) {}
    // Inherits Checked_Vector::operator[]
};
```

- Driver program

```
int main (int argc, char *argv[]) {
    try {
        size_t size = ::atoi (argv[1]);
        size_t init = ::atoi (argv[2]);
        Init_Checked_Vector<int> v (size, init);
        cout << "vector size = " << v.size ()
            << ", vector contents = ";

        for (size_t i = 0; i < v.size (); i++)
            cout << v[i];

        cout << "\n" << ++v[v.size () − 1] << "\n";
    catch (RANGE_ERROR)
    { /* ...*/ }
}
```


Multiple Inheritance Ambiguity

- Consider the following:

```
struct Base_1 { int foo (void); /* .... */ };
struct Base_2 { int foo (void); /* .... */ };
struct Derived : Base_1, Base_2 { /* .... */ };
int main (void) {
    Derived d;
    d.foo (); // Error, ambiguous call to foo ()
}
```

- There are two ways to fix this problem:

1. Explicitly qualify the call, by prefixing it with the name of the intended base class using the scope resolution operator, *e.g.*,

   ```
   d.Base_1::foo (); // or d.Base_2::foo ()
   ```

2. Add a new method foo to class Derived (similar to Eiffel's renaming concept) *e.g.*,

   ```
   struct Derived : Base_1, Base_2 {
       int foo (void) {
           Base_1::foo (); // either, both
           Base_2::foo (); // or neither
       }
   };
   ```


Summary

- Inheritance supports evolutionary, incremental development of reusable components by specializing and/or extending a general interface/implementation

- Inheritance adds a new dimension to data abstraction, *e.g.*,
  – Classes (ADTs) support the expression of *commonality* where the *general* aspects of an application are encapsulated in a few *base classes*
  – Inheritance supports the development of the application by *extension* and *specialization* without affecting existing code...

- Without browser support, navigating through complex inheritance hierarchies is difficult...