Dynamic Binding C++

Douglas C. Schmidt

Professor
d.schmidt@vanderbilt.edu
www.dre.vanderbilt.edu/∼schmidt/

Department of EECS
Vanderbilt University
(615) 343-8197

Motivation

- When designing a system it is often the case that developers:
  1. Know what class interfaces they want, without precisely knowing the most suitable representation
  2. Know what algorithms they want, without knowing how particular operations should be implemented
- In both cases, it is often desirable to *defer* certain decisions as long as possible
  - Goal: reduce the effort required to change the implementation once enough information is available to make an informed decision

Motivation (cont'd)

- Therefore, it is useful to have some form of abstract "place-holder"
  - Information hiding & data abstraction provide compile-time & link-time place-holders
    - *i.e.*, changes to representations require recompiling and/or relinking...
  - Dynamic binding provides a *dynamic* place-holder
    - *i.e.*, defer certain decisions until run-time *without* disrupting existing code structure
    - Note, dynamic binding is orthogonal to dynamic linking...
- Dynamic binding is less powerful than pointers-to-functions, but more comprehensible & less error-prone
  - *i.e.*, since the compiler performs type checking at compile-time

Motivation (cont'd)

- Dynamic binding allows applications to be written by invoking *general* methods via a base class pointer, *e.g.*,

```
class Base { public: virtual int vf (void); };
Base *bp = /* pointer to a subclass */;
bp->vf ();
```

- However, at *run-time* this invocation actually invokes more *specialized* methods implemented in a derived class, *e.g.*,

```
class Derived : public Base
{ public: virtual int vf (void); };
Derived d;
bp = &d;
bp->vf (); // invokes Derived::vf()
```

- In C++, this requires that both the general and specialized methods are virtual methods

Motivation (cont'd)

- Dynamic binding facilitates more flexible and extensible software architectures, *e.g.*,
  - Not all design decisions need to be known during the initial stages of system development
    - *i.e.*, they may be postponed until run-time
  - Complete source code is not required to extend the system
    - *i.e.*, only headers & object code
- This aids both *flexibility* & *extensibility*
  - Flexibility = 'easily recombine existing components into new configurations'
  - Extensibility = "easily add new components"

Dynamic vs. Static Binding

- *Inheritance review*
  - A pointer to a derived class can always be used as a pointer to a base class that was inherited *publicly*
    - Caveats:
    - The inverse is not necessarily valid or safe
    - *Private* base classes have different semantics...
  - *e.g.*,

```
template <typename T>
class Checked_Vector : public Vector<T> { ... };
Checked_Vector<int> cv (20);
Vector<int> *vp = &cv;
int elem = (*vp)[0]; // calls operator[] (int)
```

  - A question arises here as to which version of operator[] is called?

Dynamic vs. Static Binding (cont'd)

- The answer depends on the type of binding used...

1. *Static Binding*: the compiler uses the type of the pointer to perform the binding at compile time. Therefore, **`Vector::operator[](vp, 0)`** will be called
2. *Dynamic Binding*: the decision is made at run-time based upon the type of the actual object. **`Checked_Vector::operator[]`** will be called in this case as **`(*vp->vptr[1])(vp, 0)`**

- Quick quiz: how must class Vector be changed to switch from static to dynamic binding?

Dynamic vs. Static Binding (cont'd)

- When to chose use different bindings
  - *Static Binding*
    - Use when you are sure that any subsequent derived classes will not want to override this operation dynamically (just redefine/hide)
    - Use mostly for reuse or to form "concrete data types"
  - *Dynamic Binding*
    - Use when the derived classes may be able to provide a different (*e.g.*, more functional, more efficient) implementation that should be selected at run-time
    - Used to build dynamic type hierarchies & to form "abstract data types"

Dynamic vs. Static Binding (cont'd)

- *Efficiency* vs. *flexibility* are the primary tradeoffs between static & dynamic binding
- Static binding is generally more efficient since
  1. It has less time & space overhead
  2. It also enables method inlining
- Dynamic binding is more flexible since it enables developers to extend the behavior of a system transparently
  - However, dynamically bound objects are difficult to store in shared memory

Dynamic Binding in C++

- In C++, dynamic binding is signaled by explicitly adding the keyword **`virtual`** in a method declaration, *e.g.*,

```
struct Base {
  virtual int vf1 (void) { cout << "hello\n"; }
  int f1 (void);
};
```

  – Note, virtual methods *must* be class methods, *i.e.*, they cannot be:
    * Ordinary “stand-alone” functions
    * class data
    * Static methods

- Other languages (*e.g.*, Eiffel) make dynamic binding the default...
  – This is more flexible, but may be less efficient

C++ Virtual Methods

- Virtual methods have a fixed *interface*, but derived *implementations* can change, *e.g.*,

```
struct Derived_1 : public Base
{ virtual int vf1 (void) { cout << "world\n"; } };
```

- Supplying **virtual** keyword is optional when overriding **vf1()** in derived classes, *e.g.*,

```
struct Derived_2 : public Derived_1 {
  int vf1 (void) { cout << "hello world\n"; } // Still virtual
  int f1 (void); // not virtual
};
```

- You can declare a virtual method in any derived class, *e.g.*,

```
struct Derived_3 : public Derived_2 {
  virtual int vf2 (int); // different from vf1!
  virtual int vf1 (int); // Be careful!!!!
};
```


C++ Virtual Methods (cont'd)

- Virtual method dispatching uses object's "dynamic type" to select the appropriate method that is invoked at run-time
  - The selected method will depend on the class of the *object* being pointed at & *not* on the pointer type
- *e.g.*,

```
void foo (Base *bp) { bp->vf1 (); /* virtual */ }
Base b;
Base *bp = &b;
bp->vf1 (); // prints "hello"
Derived_1 d;
bp = &d;
bp->vf1 (); // prints "world"
foo (&b); // prints "hello"
foo (&d); // prints "world"
```

C++ Virtual Methods (cont'd)

- virtual methods are dynamically bound and dispatched at run-time, using an index into an array of pointers to class methods
  - Note, this requires only constant overhead, regardless of the inheritance hierarchy depth...
  - The virtual mechanism is set up by the constructor(s), which may stack several levels deep...
- *e.g.*,

```
void foo (Base *bp) {
  bp->vf1 ();
  // Actual call
  // (*bp->vptr[1])(bp);
}
```

- Using virtual methods adds a small amount of time & space overhead to the class/object size and method invocation time

Shape Example

- The canonical dynamic binding example:
  - *Describing a hierarchy of shapes in a graphical user interface library*
  - *e.g.*, Triangle, Square, Circle, Rectangle, Ellipse, *etc.*
- A conventional C solution would

1. Use a union or variant record to represent a **Shape** type
2. Have a type tag in every **Shape** object
3. Place special case checks in functions that operate on Shapes
   - *e.g.*, functions that implement operations like rotation & drawing

C Shape Example Solution

```
typedef struct {
  enum { CIRCLE, TRIANGLE, RECTANGLE, /* ... */
  } type_;
  union {
    struct Circle { /* .... */ } c_;
    struct Triangle { /* .... */ } t_;
    struct Rectangle { /* .... */ } r_;
    // ...
  } u_;
} Shape;
void rotate_shape (Shape *sp, double degrees) {
  switch (sp->type_) {
  case CIRCLE: return;
  case TRIANGLE: // Don't forget to break!
  // ...
  }
}
```


Problems with C Shape Example Solution

- It is difficult to extend code designed this way:
  - *e.g.*, changes are associated with functions and algorithms
  - Which are often “unstable” elements in a software system design & implementation
  - Therefore, modifications will occur in portions of the code that switch on the type tag
- Using a switch statement causes problems, *e.g.*,
- Setting & checking type tags
  - Falling through to the next case, *etc*...

Problems with C Shape Example Solution (cont'd)

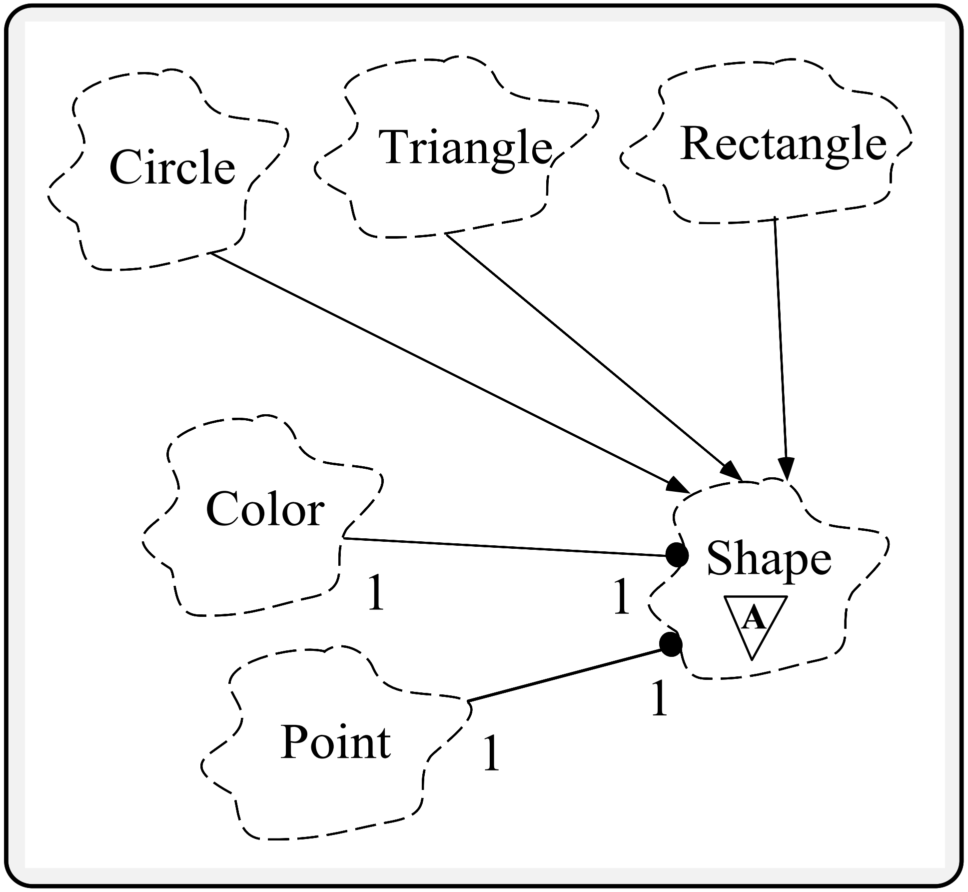
- Data structures are "passive"
  - *i.e.*, functions do most of processing work on different kinds of Shapes by explicitly accessing the appropriate fields in the object
  - This lack of information hiding affects maintainability
- Solution wastes space by making worst-case assumptions *wrt* structs & unions
- Must have source code to extend the system in a portable, maintainable manner

Object-Oriented Shape Example

- An object-oriented solution uses inheritance & dynamic binding to derive specific shapes (*e.g.*, **`Circle`**, **`Square`**, **`Rectangle`**, & **`Triangle`**) from a general Abstract Base class (ABC) called **`Shape`**
- This approach facilities a number of software quality factors:

1. Reuse
2. Transparent extensibility
3. Delaying decisions until run-time
4. Architectural simplicity

Object-Oriented Shape Example (cont'd)



- Note, the "OOD challenge" is to map arbitrarily complex system architectures into inheritance hierarchies

C++ Shape Class

```
// Abstract Base class & Derived classes for Shape.
class Shape {
public:
  Shape (double x, double y, Color &c)
    : center_ (Point (x, y)), color_ (c) {}
  Shape (Point &p, Color &c): center_ (p), color_ (c) {}
  virtual int rotate (double degrees) = 0;
  virtual int draw (Screen &) = 0;
  virtual ˜Shape (void) = 0;
  void change_color (Color &c) { color_ = c; }
  Point where (void) const { return center_; }
  void move (Point &to) { center_ = to; }
private:
  Point center_;
  Color color_;
};
```

C++ Shape Class (cont'd)

- Note, certain methods only make sense on subclasses of class Shape
  - *e.g.*, **`Shape::rotate()`** & **`Shape::draw()`**
- The **`Shape`** class is therefore defined as an *abstract base class*
  - Essentially defines only the class interface
  - Derived (*i.e.*, *concrete*) classes may provide multiple, different implementations

Abstract Base Classes (ABCs)

- ABCs support the notion of a general concept (*e.g.*, **`Shape`**) of which only more concrete object variants (*e.g.*, **`Circle`** & **`Square`**) are actually used
- ABCs are only used as a base class for subsequent derivations
  - Therefore, it is illegal to create objects of ABCs
  - However, it *is* legal to declare pointers or references to such objects...
  - ABCs force *definitions* in subsequent derived classes for undefined methods
- In C++, an ABC is created by defining a class with at least one "pure virtual method"

Pure Virtual Methods

- Pure virtual methods must be methods
- They are defined in the base class of the inheritance hierarchy, & are often never intended to be invoked directly
  - *i.e.*, they are simply there to tie the inheritance hierarchy together by reserving a slot in the virtual table...
- Therefore, C++ allows users to specify 'pure virtual methods'
  - Using the pure virtual specifier **`= 0`** indicates methods that are not meant to be *defined* in that class
  - Note, pure virtual methods are automatically inherited...

Pure Virtual Destructors

- The only effect of declaring a pure virtual destructor is to cause the class being defined to be an ABC
- Destructors are not inherited, therefore:
  - A pure virtual destructor in a base class will not force derived classes to be ABCs
  - Nor will any derived class be forced to declare a destructor
- Moreover, you will have to provide a definition (*i.e.*, write the code for a method) for the pure virtual destructor in the base class
  - Otherwise you will get run-time errors!

C++ Shape Example

- In C++, special case code is associated with derived classes, *e.g.*,

```
class Circle : public Shape {
public:
  Circle (Point &p, double rad);
  virtual void rotate (double degrees) {}
  // ...
private:
  double radius_;
};
class Rectangle : public Shape {
public:
  Rectangle (Point &p, double l, double w);
  virtual void rotate (double degrees);
  // ...
private:
  double length_, width_;
};
```

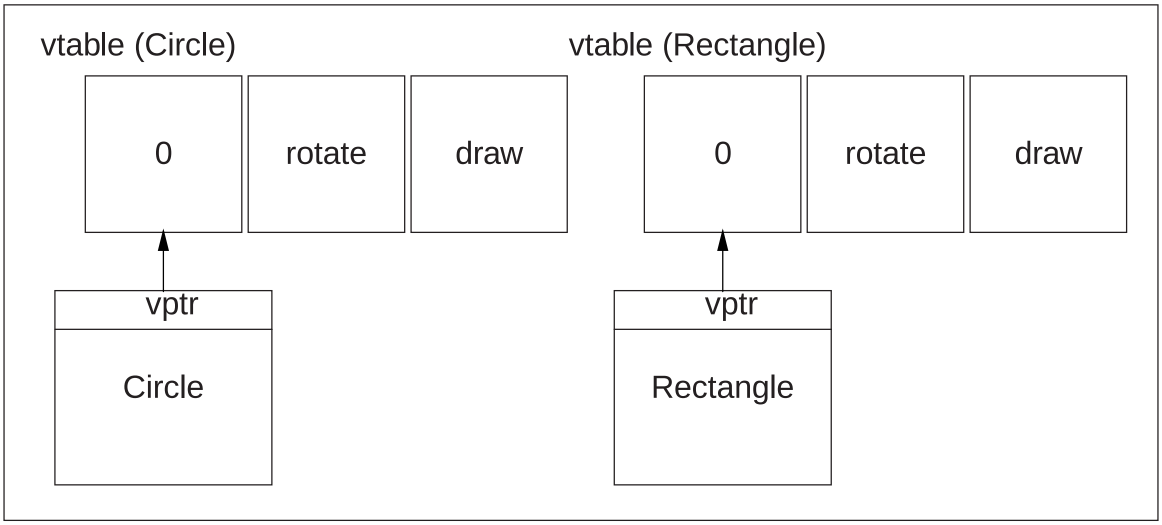
C++ Shape Example (cont'd)

- C++ solution (cont'd)
  - Using the special relationship between base classes & derived subclasses, any **Shape *** can now be "rotated" without worrying about what kind of **Shape** it points to
  - The syntax for doing this is:

```
void rotate_shape (Shape *sp, double degrees) {
  sp->rotate (degrees);
  // (*sp->vptr[1]) (sp, degrees);
}
```

  - Note, we are still "interface compatible" with original C version!

C++ Shape Example (cont'd)



- This code works regardless of what **Shape** subclass **sp** actually points to, *e.g.*,

```
Circle c;
Rectangle r;

rotate_shape (&c, 100.0);
rotate_shape (&r, 250.0);
```

C++ Shape Example (cont'd)

- The C++ solution associates specializations with derived classes, rather than with function **`rotate_shape()`**
- It's easier to add new types without breaking existing code since most changes occur in only one place, *e.g.*:

```
class Square : public Rectangle {
// Inherits length & width from Rectangle
public:
  Square (Point &p, double base);
  virtual void rotate (double degree) {
    if (degree % 90.0 != 0)
      // Reuse existing code
      Rectangle::rotate (degree);
  }
  /* .... */
};
```

C++ Shape Example (cont'd)

- We can still rotate any **Shape** object by using the original function, *i.e.*,

```
void rotate_shape (Shape *sp, double degrees)
{
  sp->rotate (degrees);
}

Square s;
Circle c;
Rectangle r;

rotate_shape (&s, 100.0);
rotate_shape (&r, 250.0);
rotate_shape (&c, 17.0);
```

Comparing the Two Approaches

- If support for **`Square`** was added in the C solution, then every place where the type tag was accessed would have to be modified
  - *i.e.*, modifications are spread out all over the place
  - Including both header files and functions
- Note, the C approach prevents extensibility if the provider of **`Square`** does not have access to the source code of function **`rotate_shape()`**!
  - *i.e.*, only the header files & object code is required to allow extensibility in C++

Comparing the Two Approaches (cont'd)

```
/* C solution */
void rotate_shape (Shape *sp, double degree) {
  switch (sp->type_) {
  case CIRCLE: return;
  case SQUARE:
    if (degree % 90 == 0)
      return;
    else
      /* FALLTHROUGH */;
  case RECTANGLE:
    // ...
    break;
  }
}
```

Comparing the Two Approaches (cont'd)

- Example function that rotates **`size`** shapes by **`angle`** degrees:

```
void rotate_all (Shape *vec[], int size, double angle)
{
  for (int i = 0; i < size; i++)
    vec[i]->rotate (angle);
}
```

- **`vec[i]->rotate (angle)`** is a virtual method call
  - It is resolved at run-time according to the actual type of object pointed to by **`vec[i]`**
  - *i.e.*,

```
vec[i]->rotate (angle) becomes
(*vec[i]->vptr[1]) (vec[i], angle);
```

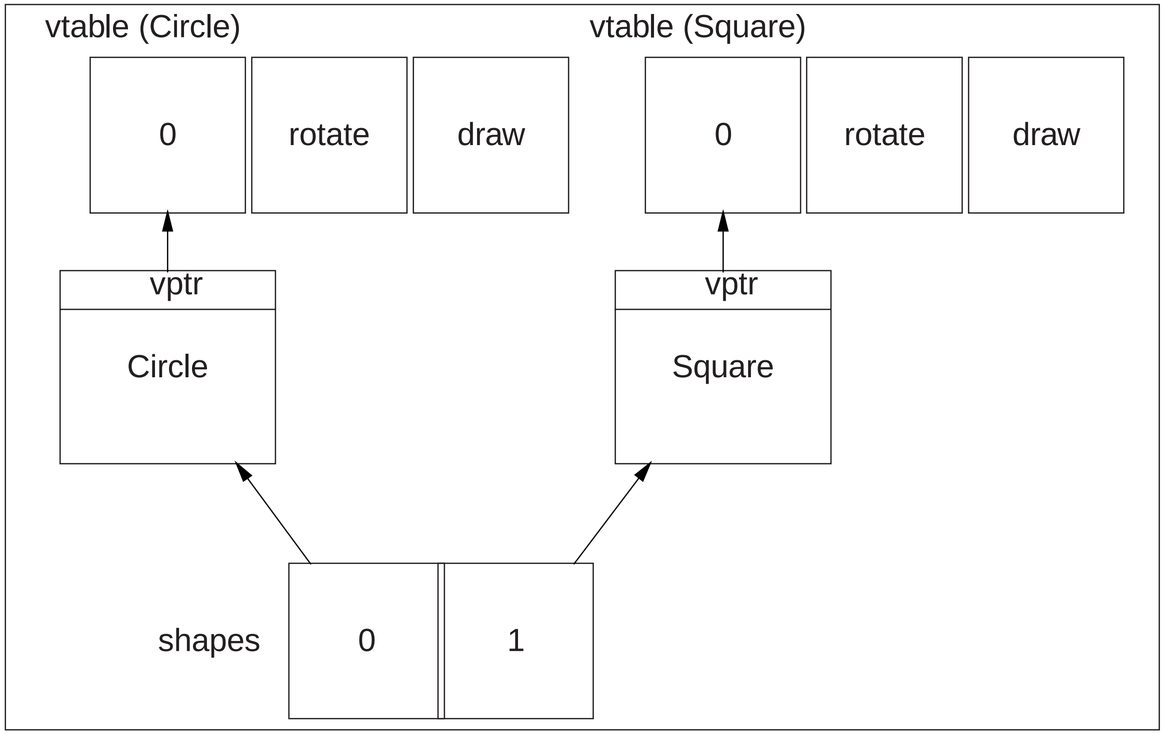
Comparing the Two Approaches (cont'd)

- Sample usage of function **`rotate_all()`** is

```
Shape *shapes[] = {
  new Circle (/* .... */),
  new Square (/* .... */)
};
int size = sizeof shapes / sizeof *shapes;
rotate_all (shapes, size, 98.6);
```

- Note, it is not generally possible to know the exact type of elements in variable **shapes** until run-time
  - However, at compile-time we know they are all derived subtypes of base class **Shape**
    - This is why C++ is not fully polymorphic, but *is* strongly typed

Comparing the Two Approaches (cont'd)



- Here's what the memory layout looks like

Comparing the Two Approaches (cont'd)

- Note that both the inheritance/dynamic binding & union/switch statement approaches provide mechanisms for handling the design & implementation of *variants*
- The appropriate choice of techniques often depends on whether the class interface is stable or not
  - Adding a new subclass is easy via inheritance, but difficult using union/switch (since code is spread out everywhere)
  - On the other hand, adding a new method to an inheritance hierarchy is difficult, but relatively easier using union/switch (since the code for the method is localized)

Calling Mechanisms

- Given a pointer to a class object (*e.g.*, **`Foo *ptr`**) how is the method call **`ptr->f (arg)`** resolved?
- There are three basic approaches:

  1. *Static Binding*
  2. *Virtual Method Tables*
  3. *Method Dispatch Tables*

- C++ & Java use both *static binding* & *virtual method tables*, whereas Smalltalk & Objective C use method dispatch tables
- Note, type checking is orthogonal to binding time...

Static Binding

- Method `f`'s address is determined at compile/link time
- Provides for strong type checking, completely checkable/resolvable at compile time
- Main advantage: the *most* efficient scheme
  - *e.g.*, it permits inline method expansion
- Main disadvantage: the *least* flexible scheme

Virtual Method Tables

- Method **`f()`** is converted into an index into a table of pointers to functions (*i.e.*, the “virtual method table”) that permit run-time resolution of the calling address
  - The **`*ptr`** object keeps track of its type via a hidden pointer (**`vptr`**) to its associated virtual method table (**`vtable`**)
- Virtual methods provide an exact specification of the type signature
  - The user is guaranteed that only operations specified in class declarations will be accepted by the compiler

Virtual Method Tables (cont'd)

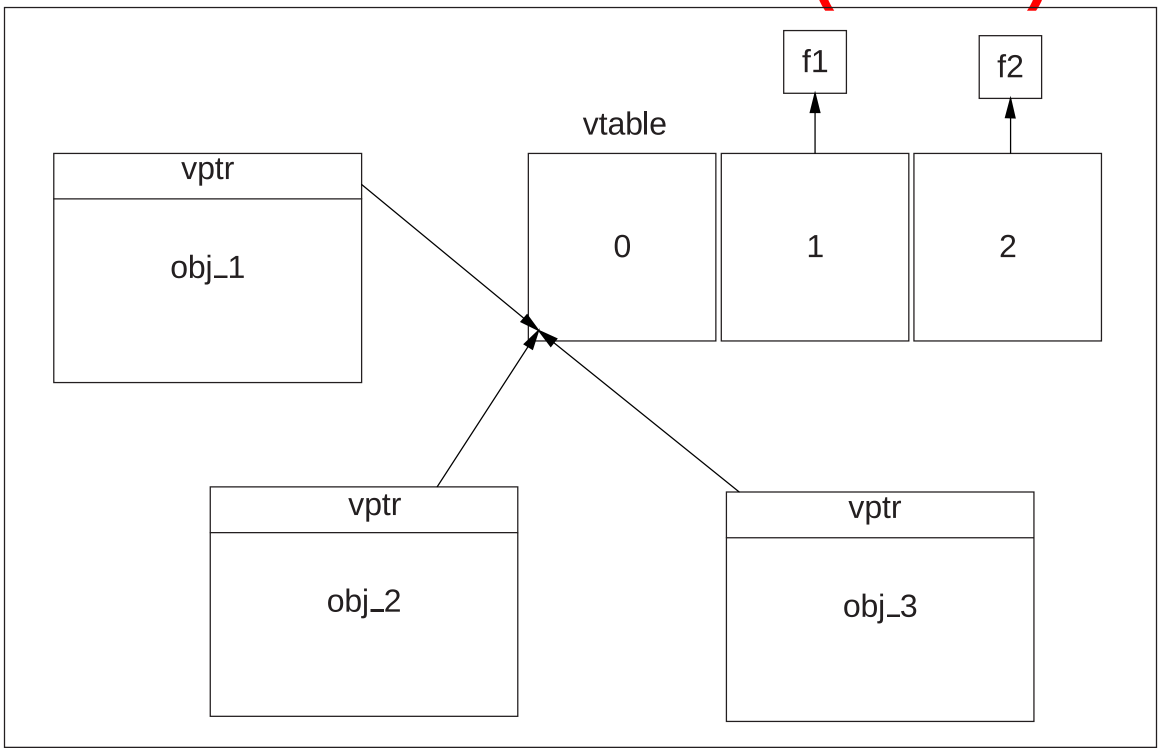
- Main advantages

  1. More flexible than static binding
  2. There only a constant amount of overhead (compared with method dispatching)
  3. *e.g.*, in C++, pointers to functions are stored in a separate table, *not* in the object!

- Main disadvantages

  – Less efficient, *e.g.*, often not possible to inline the virtual method calls...

Virtual Method Tables (cont'd)



- *e.g.*,

```
class Foo {
public:
  virtual int f1 (void);
  virtual int f2 (void);
  int f3 (void);
private:
  // data ...
};
Foo obj_1, obj_2, obj_3;
```

Method Dispatch Tables

- Method `f` is looked up in a table that is created & managed dynamically at run-time
  - *i.e.*, add/delete/change methods dynamically
- Main advantage: the most flexible scheme
  - *i.e.*, new methods can be added or deleted *on-the-fly*
  - & allows users to invoke *any* method for *any* object
- Main disadvantage: generally inefficient & not always *type-secure*
  - May require searching multiple tables at run-time
  - Some form of caching is often used
  - Performing run-time type checking along with run-time method invocation further decreases run-time efficiency
  - Type errors may not manifest themselves until run-time

Downcasting

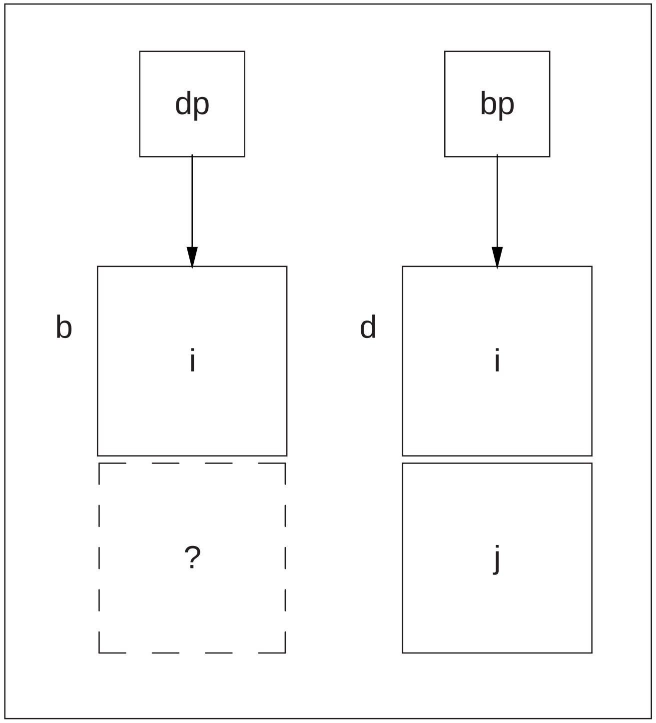
- Downcasting is defined as casting a pointer or reference of a base class type to a type of a pointer or reference to a derived class
  – *i.e.*, going the opposite direction from usual "base-class/derived-class" inheritance relationships...
- Downcasting is useful for
  1. *Cloning an object*
     – *e.g.*, required for "deep copies"
  2. *Restoring an object from disk*
     – This is hard to do transparently...
  3. 'Taking an object out of a heterogeneous collection of objects & restoring its original type'
     – Also hard to do, unless the only access is via the interface of the base class

Contravariance

- Downcasting can lead to trouble due to *contravariance*, *e.g.*:

```
struct Base {
  int i_;
  virtual int foo (void) { return i_; }
};
struct Derived : public Base {
  int j_;
  virtual int foo (void) { return j_; }
};
void foo (void) {
  Base b;
  Derived d;
  Base *bp = &d; // "OK", a Derived is a Base
  Derived *dp = &b;// Error, a Base is not necessarily a Derived
}
```

Contravariance (cont'd)



- Problem: what happens if **`dp->j_`** is referenced or set?

Contravariance (cont'd)

- Since a **`Derived`** object always has a **`Base`** part certain operations are ok:

```
bp = &d;
bp->i_ = 10;
bp->foo (); // calls Derived::foo ();
```

- Since base objects don't have subclass data some operations aren't ok
  - *e.g.*, accesses information beyond end of **`b`**:

```
dp = (Derived *) &b;
dp->j_ = 20; // big trouble!
```

- C++ permits contravariance if the programmer explicitly casts, *e.g.*,

```
dp = (Derived *) &b; // unchecked cast
```

- Programmers must ensure correct operations, however...

Run-Time Type Identification (RTTI)

- RTTI is a technique that allows applications to use the C++ run-time system to query the type of an object at run-time
  - Only supports very simple queries regarding the interface supported by a type
- RTTI is only fully supported for dynamically-bound classes
  - Alternative approaches would incur unacceptable run-time costs & storage layout compatibility problems

Run-Time Type Identification (cont'd)

- RTTI could be used in our earlier example

```
if (Derived *dp = dynamic_cast<Derived *>(&b))
  /* use dp */;
else
  /* error! */
```

- For a dynamic cast to succeed, the "actual type" of **b** would have to either be a **Derived** object or some subclass of **Derived**
- if the types do not match the operation fails at run-time
- if failure occurs, there are several ways to dynamically indicate this to the application:
  - To return a NULL pointer for failure
  - To throw an exception
  - *e.g.*, in the case of reference casts...

Run-Time Type Identification (cont'd)

- **dynamic_cast** used with references
  - A reference **dynamic_cast** that fails throws a **bad_cast** exception
- *e.g.*,

```
void clone (Base &ob1)
{
  try {
    Derived &ob2 =
      dynamic_cast<Derived &>(ob1);
    /* ... */
  } catch (bad_cast) {
    /* ... */
  }
}
```

Run-Time Type Identification (cont'd)

- Along with the **`dynamic_cast`** extension, the C++ language now contains a typeid operator that allows queries of a limited amount of type information at run-time
  - Includes both dynamically-bound and non-dynamically-bound types...
- *e.g.*,

```
typeid (type_name) yields const Type_info &
typeid (expression) yields const Type_info &
```

- Note that the *expression* form returns the *run-time type* of the expression if the class is dynamically bound...

Run-Time Type Identification Examples

```
Base *bp = new Derived;
Base &br = *bp;

typeid (bp) == typeid (Base *) // true
typeid (bp) == typeid (Derived *) // false
typeid (bp) == typeid (Base) // false
typeid (bp) == typeid (Derived) // false

typeid (*bp) == typeid (Derived) // true
typeid (*bp) == typeid (Base) // false

typeid (br) == typeid (Derived) // true
typeid (br) == typeid (Base) // false

typeid (&br) == typeid (Base *) // true
typeid (&br) == typeid (Derived *) // false
```

Run-Time Type Identification Problems

- RTTI encourages dreaded "if/else statements of death" *e.g.*,

```
void foo (Object *op) {
  if (Foobar *fbp = dynamic_cast<Foobar *> (op))
    fbp->do_foobar_things ();
  else if (Foo *fp = dynamic_cast<Foo *> (op))
    fp->do_foo_things ();
  else if (Bar *bp = dynamic_cast<Bar *> (op))
    bp->do_bar_things ();
  else
    op->do_object_stuff ();
}
```

- This style programming leads to an alternative, slower method of dispatching methods
  – *i.e.*, duplicating *vtables* in an unsafe manner a compiler can't check

Summary

- Dynamic binding enables applications & developers to defer certain implementation decisions until run-time
  - *i.e.*, which implementation is used for a particular interface
- It also facilitates a decentralized architecture that promotes flexibility & extensibility
  - *e.g.*, it is possible to modify functionality without modifying existing code
- There may be some additional time/space overhead from using dynamic binding...
  - However, alternative solutions also incur overhead, *e.g.*, the union/switch approach