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C++ Hierarchy Design Idioms

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C++ Hierarchy Design Idioms

- Hierarchy Design Idioms
  - Data abstraction
  - Base class member roles
  - Overloading, overriding, and hiding
  - Hierarchies and polymorphism
  - Conditional code
  - Substitutability
  - Totalitarianism, tough love, and reuse
  - Degenerate hierarchies
  - Design for repair
  - Composition of simple hierarchies
  - Abstract bases, slicing, and copying

The Advantage of Abstract Data Types

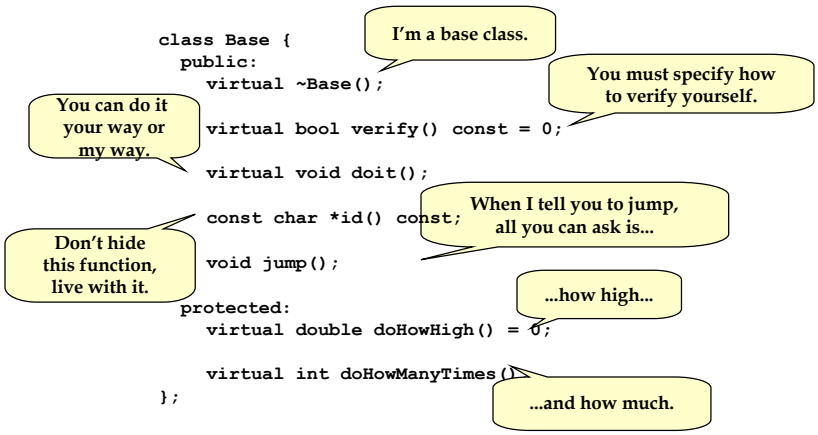
- A type is a set of operations.
- An abstract data type is set of operations with an implementation.
- When we identify objects in a problem domain, the first question we ask about them is "What can I do with this object?" not "How is this object implemented?"
- If a natural description of a problem involves employees, contracts, and payroll records, then the programming language used to solve the problem should contain `Employee`, `Contract`, and `PayrollRecord` types.
- This allows an efficient, two-way translation between the problem domain and the solution domain.
- Software written this way has less "translation noise," and is simpler and more correct.
- *The purpose of an abstract data type is to extend the programming language into the problem domain.*

Creating an Abstract Data Type

- Choose a descriptive name for the type.
  - If you have trouble choosing a name for the type, you don't know enough about what you want to implement to design an abstract data type.
  - An abstract data type should represent a single, well-defined concept.
- List the operations that the type can perform.
  - An abstract data type is defined by what you can do with it.
  - Remember initialization, cleanup, copying, and conversions.
- Design an interface for the type.
  - The type should be "easy to use correctly, hard to use incorrectly."
  - Look out for language-specific pitfalls.
  - An abstract data type extends the language; do proper language design.
  - Put yourself in the place of the user of your type.
- Implement the type.
  - Don't let the implementation affect the interface of the type.
  - Implement the contract promised by the type's interface.

Bossy Bases

- **Well-designed base classes tell derived classes how they may customize or extend the base class.**




```
class Base {
  public:
    virtual ~Base();

    virtual bool verify() const = 0;

    virtual void doit();

    const char *id() const;

    void jump();

  protected:
    virtual double doHowHigh() = 0;

    virtual int doHowManyTimes()
};
```

- *Design totalitarian base classes.*
- *When deriving, bend to the will of the base class.*

The Template Method Pattern

- **A template method partitions an algorithm into invariant and variant parts.**
  - **The invariant part is defined in a base class.**
  - **The variant parts of the algorithm are provided as virtual functions that may be overridden in derived classes.**

```
class Base {
  public:
    //…
    void algorithm();
  protected:
    virtual bool doHook1() const;
    virtual void doHook2() = 0;
};
void Base::algorithm() {
    //…
    if( doHook1() ) {
        //…
        doHook2();
    }
    //…
}
```

- **A template method gives the base class designer a level of control somewhere between a non-virtual and virtual function.**

NVI

- Use of Template Method can be pushed to its logical extreme: the non-virtual interface idiom.
- The public interface is entirely non-virtual (except the destructor).

```
class Base {
  public:
    virtual ~Base();
    bool verify() const = 0;
    void doit();
    const char *id() const;
    void jump();
  private:
    virtual bool doVerify() const = 0;
    virtual void doDoit();
    virtual double doHowHigh() = 0;
    virtual int doHowManyTimes();
};
```

- This doesn't affect the user of the Base interface.
- This allows "pre" and "post" code to be added in the base class that affects all overriding derived classes.

Common Sense

- A base class doesn't *always* have to have a virtual destructor.

```
namespace std {
    template <class Arg, class Res>
    struct unary_function {
        typedef Arg argument_type;
        typedef Res result_type;
    };
}

namespace Loki {
    struct OpNewCreator {
        template <class T>
        static T *Create() { return new T; }
      protected:
        ~OpNewCreator() {}
    };
}
```

- Just make sure that your base class really is one of these exceptional cases.

Review: Overloading, Overriding, and Hiding

- Overloading and overriding are two entirely separate concepts.
- Function overloading refers to a set of functions in the same scope that have the same name and different signatures.

```
class Base {
    void f();
    virtual void f( int );
};
```

- Overriding refers to a derived class function that has the same name and signature as a base class virtual function.

```
class Derived : public Base {
    void f( int );
};
```

- A name in an inner scope hides the same name in outer scopes.

```
class Derived2 : public Derived {
    int f;
};
Derived2 *d2p = something;
d2p->f( 12 ); // error! f is not a function
d2p->Derived::f( 12 ); // OK
```

- *Careless combination of overloading, overriding, and hiding can make code difficult to understand and maintain.*

Hiding Base Class Non-Virtuals

- A base class non-virtual function specifies an invariant that applies to all derived classes.
- Hiding a base class non-virtual raises the complexity of the hierarchy, and will lead to misunderstanding and error.

```
class B {
  public:
    void f();
    void f( int );
};
class D : public B {
  public:
    void f();
};

B *bp = new D;
bp->f(); // oops! called B::f() for D object
D *dp = new D;
dp->f( 123 ); // error! B::f(int) hidden
```

- Hiding non-virtuals defeats polymorphism; different interfaces to the same object give different behavior.
- *Do not hide base class non-virtuals.*

Overloading Virtual Functions

- **Be careful about overloading virtual functions.**
- **A set of overloaded virtual functions in the base class will be hidden by a single overriding function in a derived class.**
- **This will result in different functions being called depending on the static type used to call the function.**

```
class Base {
  public:
    virtual void f( double );
    virtual void f( int );
};
class Derived : public Base {
  public:
    void f( int );
};
// ...
Derived *dp = new Derived;
Base *bp = dp;
bp->f( 12.3 ); // calls Base::f( double )
dp->f( 12.3 ); // calls Derived::f( int )!!!
```

- *Don't overload virtual functions.*

Overloading Virtual Functions

- **If you need an overloaded member function name, overload non-virtual member functions that "kick down" to differently-named virtual functions.**

```
class Base {
  public:
    void f( double );
    void f( int );
  protected:
    virtual void f_double( double );
    virtual void f_int( int );
};
inline void f( int i ) { f_int( i ); }
inline void f( double d ) { f_double( d ); }
```

- **Derived classes may then override a single base class function without hiding all the others.**

Virtual Functions and Default Initializers

- A function's signature does not include default argument initializers.
- A base class virtual with a default initializer can be overridden by a derived class function without a default initializer, or with a different default initializer. This can lead to confusion.

```
class Base {
  public:
    virtual void f( int = 12 );
    virtual void g( int = 10 );
};
class Derived : public Base {
  public:
    void f( int );
    void g( int = 5 );
};
// ...
Derived *dp = new Derived;
Base *bp = dp;
bp->f(); // calls Derived::f( 12 )
dp->f(); // error!
bp->g(); // calls Derived::g( 10 )!
dp->g(); // calls Derived::g( 5 )
```

- *Avoid default argument initializers for virtual functions.*

Abstract and Concrete Classes

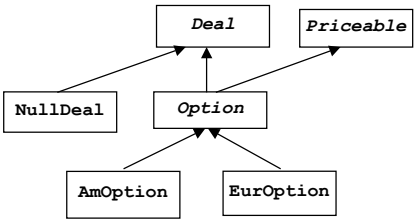
- An abstract class can not be used to instantiate an object.
- Base classes represent abstract concepts, and should therefore be abstract.
  - there are no "employees" in the problem domain, so there shouldn't be any `Employee` objects
  - there are no "symbol tables" in the compiler, only specific types of symbol table
- Generic code should be written to a base class's interface, without making the assumption that it is dealing precisely with a base class.
- Concrete base classes may give rise to low-level problems.
  - Slicing!
  - Hard to implement copy operations.
- *Class hierarchies should be designed with abstract base classes and concrete leaves.*

Where Do Hierarchies Come From?

- We may recognize a hierarchy from the top, through specialization.
  - "Our application deals with employees." "What kind of employees are there?" "The usual: hourly, salaried, and probably some others in the future."
- We may recognize a hierarchy from the bottom, through abstraction.
  - "I've got a class table, a function table, and a global table, and they all have different implementations." "Have they got anything in common?" "Well, they all behave like symbol tables."
- We may recognize a hierarchy late in development, from implementation issues.
  - "I've got a Widget object that may be in my local memory, in shared memory, or on another node in the network. I'm getting pretty tired of special casing every time I want to access a Widget." "Don't."

The Meaning of Polymorphism

- Consider a type of financial option, `AmOption`.
- It is simultaneously an `AmOption`, an `Option`, a `Deal`, and a `Priceable`.
- This means it can respond to messages sent to any of its four interfaces.



- This means that an `AmOption` can leverage generic code written to any of its base classes' interfaces.
- Our hierarchy design heuristics tell us how to craft class hierarchies to make this possible.

Static and Dynamic Binding

- Polymorphism depends on dynamic binding.
- Static binding determines what function is going to be called at compile time, based on the declared type of the object.

```
Employee *ep = getNextEmployee();
cout << ep->getName() << endl; // calls Employee::getName
```

- Dynamic binding waits until runtime to determine what function to call.

```
Deal *dp = getNextDeal();
dp->validate(); // calls some sort of validate...
```

- Typically, the function called depends on the type of a single object (single dispatch).
- It's also possible to implement dynamic binding based on the types of multiple objects (multiple dispatch).
- *An object should exhibit the same behavior no matter which of its interfaces is used to manipulate it.*

```
AmOption *d = new AmOption;
Option *b = d;
d->price();
b->price(); // should be same behavior!
```


Type-Based Conditionals

- We don't switch on type codes in object-oriented programs.

```
void process( Employee *e ) {
    switch( e->type() ) { // evil code!
    case SALARY: fireSalary( e ); break;
    case HOURLY: fireHourly( e ); break;
    case TEMP: fireTemp( e ); break;
    default: throw UnknownEmployeeType();
}
```

- The polymorphic approach is more appropriate.

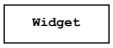
```
void process( Employee *e )
    { e->fire(); }
```

- The advantages are enormous:
  - It's simpler.
  - It doesn't have to be to be recompiled as new employee types are added.
  - It is impossible to have type-based runtime errors.
  - It's probably faster and smaller!
- *Implement type-based decisions with dynamic binding, not with conditional control structures.*

Avoiding Control Structures with Dynamic Binding

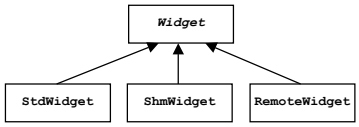
- One way to avoid making an incorrect decision is not to make a decision.
- Many conditional constructs can be "encoded" in a class hierarchy.

Before




```
if( Widget is in local memory )
    w->process();
else if( Widget is in shared memory )
    do horrible things to process it
else if( Widget is remote )
    do even worse things to process it
else
    error();
```

After

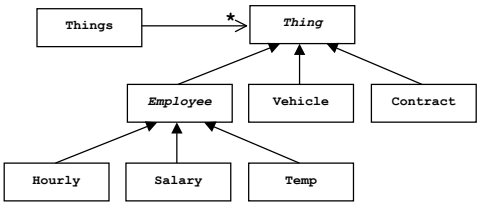



```
w->process();
```

- We effectively convert conditional code into type-based code.
- *Convert conditional control structures into type-based decisions where appropriate.*

Cosmic Hierarchies

- Overly-inclusive hierarchies are generally bad design.



- Such hierarchies tend to give rise to "containers of anything."
- Type information is lost, and must be recovered through conditional code.
  - "Ok, thing, I'm going to process you. Are you a vehicle?" "No." "All right, are you a contract?" "Nope." "Well, perhaps you're an employee?" "Wrong again." "I give up!"
- This kind of conditional code is particularly inefficient, hard to maintain, and prone to error.
- Such hierarchies may also be inefficient.
- *Avoid cosmic hierarchies.*

Some Bad Code

```
void process( Thing *a ) {
    if( Vehicle *v = dynamic_cast<Vehicle *>(a) )
        v->drive();
    else if( Contract *c = dynamic_cast<Contract *>(a) )
        c->enforce();
    else if( Employee *e = dynamic_cast<Employee *>(a) )
        e->fire();
    else
        throw UnknownAssetType( a );
}

void doThings( list<Thing *> things ) {
    for( list<Thing *>::iterator i(things.begin); i != things.end(); ++i )
        try {
            process( *i );
        }
        catch( UnknownThing &ut ) {
             // ???
        }
}
```


Casting for Flexibility and Disaster

- **In order to add functionality, users of the `Thing` hierarchy may have to resort to type-based conditional code.**

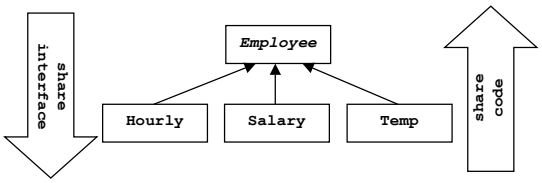
```
void process( Thing *a ) {
    if( Vehicle *v = dynamic_cast<Vehicle *>(a) )
        v->drive();
    else if( Contract *c = dynamic_cast<Contract *>(a) )
        c->enforce();
    else if( Employee *e = dynamic_cast<Employee *>(a) )
        e->fire();
    else
        throw UnknownThing( a );
}
```

- **This approach is both slow and difficult to maintain.**
- **Alternatively, the `Thing` hierarchy can provide a hook for a Visitor pattern implementation.**

```
class ThingVisitor;
class Thing {
  public:
    void accept( ThingVisitor & ) = 0;
    //…
};
```

Hierarchies and Reuse

- Class hierarchies promote reuse in two ways.
  - code sharing
  - interface sharing
- We get code sharing by putting common derived class implementations in base classes. This is good.



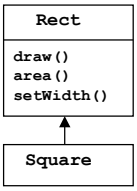
- We get interface sharing by writing substitutable derived classes. This is better.
- *Interface sharing is more important than code sharing. Don't sacrifice the base class interface in order to share code.*

Is-A Relationships

- Public inheritance is used to model the is-a relationship.
- Fine. What does the is-a relationship model?
- Is-a does not *necessarily* mean specialization.
  - a `Stack` is not a `List`
- Is-a does not *necessarily* mean subset.
  - a `Circle` is not necessarily an `Ellipse`
- On the other hand, an is-a relationship may hold between two types that are not logically related, or whose relationship emerged after analysis, during design.
  - a `Model` is not a `DisplayProtocol`, but a `Model` is-a `DisplayProtocol` if it responds to the display protocol
  - a `Person` is not a `Persistent`, but a `Person` is-a `Persistent` if it can be saved to disk
- Is-a means substitutable.
- *Public inheritance should imply substitutability.*

Isa Relationships and Substitutability

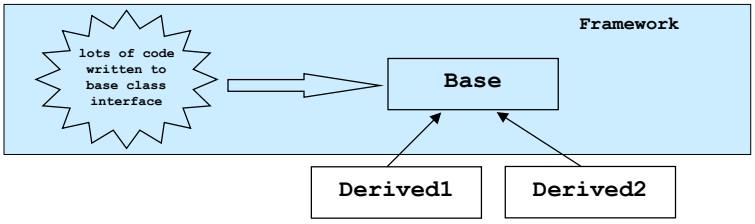
- When we analyze a domain, we may recognize isa relationships, and enshrine them in hierarchies.
  - a salaried employee isa employee
  - a function symbol table isa symbol table
  - a square isa rectangle
- However, substitutability is a low-level property of a hierarchy.
  - it depends on the set of operations promised by the base class
  - it depends on the current and future uses of the base class interface by generic code
- For instance, a `Square` may not be a `Rectangle`.
- Our base class design heuristics tell us how to communicate the requirements for substitutability to derived class designers.



- *Substitutability is the most important property of a class hierarchy.*

The Contract

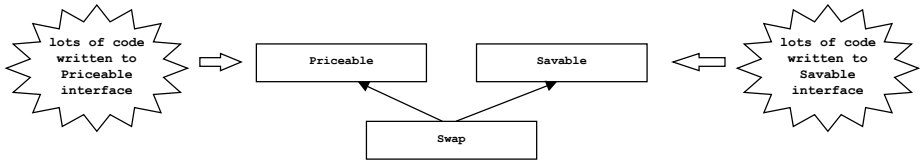
- A base class establishes a contract between generic code written to the contract and derived classes that implement the contract.



- The generic code knows nothing about the derived classes.
- The generic code may have been compiled long before the derived classes existed.
- The authors of the generic code and base class may have no knowledge of or control over the derived classes.
- *The contract provided by the base class is what allows the derived classes and generic code to work together.*

Totalitarianism, Substitutability, and Tough Love

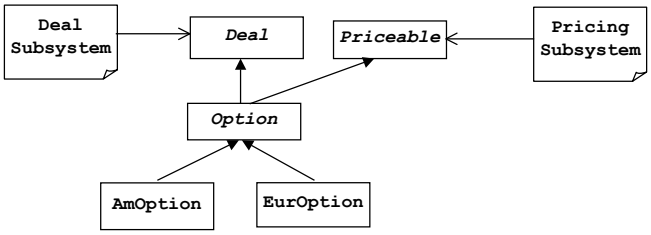
- **Most code is written in terms of abstract base class interfaces.**



- **The only way this can work is if *every* derived class is *always* substitutable for *each* of its public base classes.**
- **The only way this can work is if base classes are hard on the derived classes, and if derived classes listen to and obey the base classes.**

Contracts and Leveraging Generic Code

- **A base class specifies a contract.**
  - **generic code is written to the base class interface**
  - **derived classes customize the generic code by being substitutable for the base class**



- **The greatest reuse is achieved by leveraging entire subsystems with substitutable derived classes.**
- *Base class design is about writing clear contracts.*
- *Derived class design is about fulfilling base class contracts.*
- *The base class is ignorant of its derived classes.*

Attaching Interfaces

- Consider the following interface classes.

```
class Saveable { // persistent interface
    virtual void save() = 0;
    // ...
};
class Priceable { // pricing interface
    virtual void price() = 0;
    // ...
};
```

- These interface classes would commonly be used to attach attributes to classes in a single inheritance hierarchy.

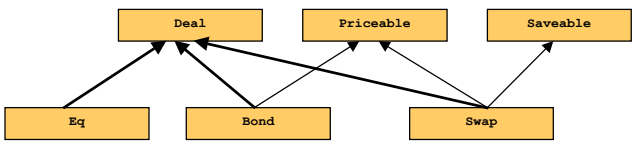
```
class Deal {
  public:
    virtual void validate() = 0;
    //...
};
class Bond : public Deal, public Priceable {
  public:
    void validate();
    void price();
    //...
};
class Swap : public Deal, public Priceable, public Saveable
    {/*...*/};
```


`dynamic_cast` as the Downcast of Doom

- Consider adding a new capability without changing or recompiling the hierarchy.
- Naive code might simply ask the obvious questions.

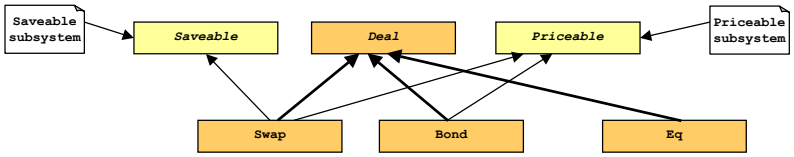
```
void processDeal( Deal *d ) {
    d->validate();
    if( Bond *b = dynamic_cast<Bond *>(d) )
        b->price();
    else if( Swap *s = dynamic_cast<Swap *>(d) ) {
        s->price();
        s->save();
    }
}
```

- This code is very fragile, slow, and hard to maintain.



Capability Queries

- A common organization in OOD is to attach "capabilities" to classes in a hierarchy through multiple inheritance.



- This is fine.
- The interface classes represent a set of operations; a capability. A successful cross-cast to the interface type indicates that the unknown concrete class has that capability.

```
Deal *dp = getNextDeal();
Priceable *pp = dynamic_cast<Priceable *>(dp); //can you be priced?
if( pp ) {
    // yup.
}
else {
    // nope.
}
```

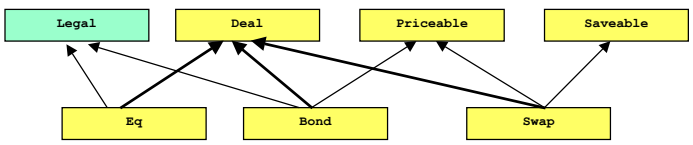
- This is usually a bad idea.

Capability Queries as a Stopgap

- A `dynamic_cast` can be used to ask if a particular `Deal` object, referred to through a base class pointer, may be priced and/or is persistent.

```
void processDeal( Deal *d ) {
    d->validate();
    if( Priceable *p = dynamic_cast<Priceable *>(d) )
        p->price();
    if( Saveable *s = dynamic_cast<Saveable *>(d) )
        s->save();
}
```

- This code is somewhat less fragile.
- It's still slow and dangerous.
- Capability queries are not a good base for a design; they are a hack.



A Better Design

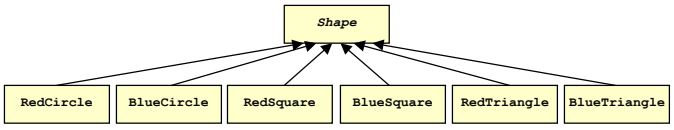
- **Remember OOD 101?**

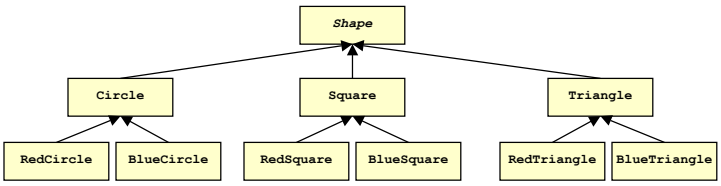
```
class Deal {
  public:
    virtual void validate() = 0;
    virtual void process() = 0;
    //...
};
class Bond : public Deal, public Priceable {
  public:
    void validate();
    void price();
    void process()
        { validate(); price(); }
};
class Swap : public Deal, public Priceable, public Saveable {
  public:
    void validate();
    void price();
    void save();
    void process()
        { validate(); price(); save(); }
};
```

- **This code is (much) faster and simpler, but we had to modify the hierarchy.**

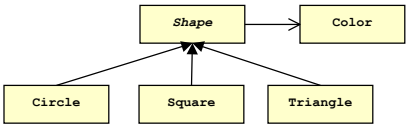
Exponentially Expanding Hierarchies

- **A common error among new OO designers is to overuse inheritance.**



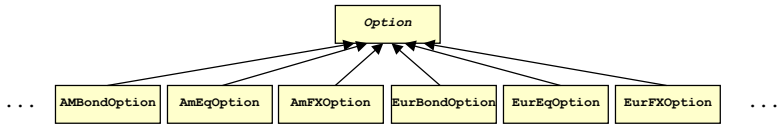


- **Composition, or composition of simpler hierarchies, is usually a better choice.**

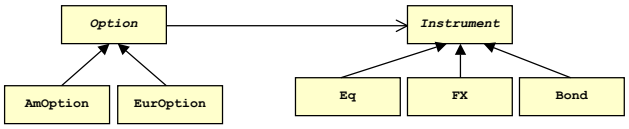


Wide or Deep Hierarchies

- A very wide or very deep inheritance hierarchy usually indicates a design flaw.
- A hierarchy that exhibits "exponential expansion" during maintenance usually indicates a design flaw.



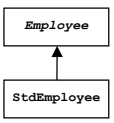
- Generally, the correct design involves composition of simpler hierarchies.



- *Avoid overusing inheritance.*
- *Use composition of simple hierarchies rather than monolithic hierarchies.*

Base Classes and Standalone Classes are Different

- There are three types of classes.
  - abstract base classes
  - concrete derived classes
  - standalone classes
- The design heuristics for each of these three types of class are very, very different. Decide what you're trying to design before you design it.
- Client code treats base classes very differently from standalone classes.
- Standalone classes that later become base classes wreak havoc on using code. Start a potential base class off as an abstract base class.



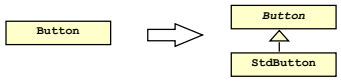
- *Classes that are part of a hierarchy and standalone classes come from different planets.*
- *Degenerate hierarchies are your friends.*

Framework-Oriented Design

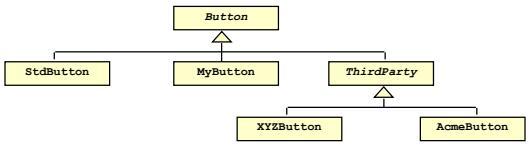
- Every significant application has variations, either in "space" or in time.
- Framework-oriented design deals well with these issues.
  - supports the open/closed principle (Meyer)
  - "build for today, design for tomorrow" (Goldfedder)
- It is a mistake to write an application.
  - every significant application should be designed as a framework.
  - patterns help a lot here, but remember to be wary of the hype.

Degenerate Hierarchies

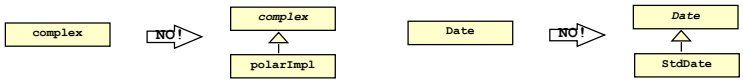
- Recognizing that a class *may* become a base class in the future, and transforming it into a simple two-class hierarchy, is an example of "designing for the future."



- The alternative of initially employing a concrete class, and introducing derived types later, would force us, or our users, to rewrite existing framework code.



- Obviously, this transformation does not make sense for every concrete class. As designers, we must use our judgement.

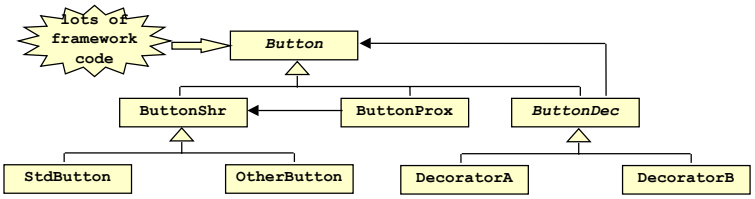


Inheritance for Code Reuse

- **Inheritance is primarily about interface reuse, not code reuse.**
- **Use of inheritance *solely* for the purpose of reusing base class implementations in derived classes often results in unnatural, unmaintainable, and ultimately more inefficient designs.**
- **A priori use of inheritance for code reuse will result in less code sharing than use of inheritance for interface reuse.**
- ***Concentrate on inheritance of interface. Proper and efficient code reuse will follow automatically.***

Contradictory Design Forces

- **Sharing common code in base classes is good.**
- **Leveraging the base class interface is better.**
- **Can we have both?**



- **This introduces an "artificial" class into the hierarchy, but may *sometimes* be justified.**

Observations

- Design patterns are often selected for "force resolution," but knowledge of their existence is also a force on the structure of a hierarchy.
- Composition of simple parts is simpler than a monolithic design, but can represent a more complex structure.
- Designs that promote ignorance and a single point of change are good.
- Code the minimum, but design toward the future.
- Maximum flexibility is not a goal, reasonable flexibility is.
- Idioms are useful only if they are both generally used and sometimes disregarded.
- There is no substitute for thoughtful abstraction and careful design. There are no cookbooks for OOD.

More Information

- Steve Dewhurst is the author of numerous technical articles on C++ programming techniques and compiler design, is the author of *C++ Gotchas* and *C++ Common Knowledge*, and is co-author of *Programming in C++*. He is a frequent speaker at industry conferences, a principal lecturer at *The* C++ Seminar, is on the advisory board for *The C++ Source*, and is a contributing editor for *The C/C++ Users Journal*.
- Steve has written C++ compilers for both Bell Labs and Glockenspiel, Ltd.,was a member of the editorial board and columnist for *C++ Report*, and was a founder, columnist, and member of the editorial board of *The C++ Journal*.
- Steve has mentored and consulted with C++/OO projects ranging in size from 1 to over 100 developers, in areas ranging from compilers to image processing, e-commerce, and securities trading.
- Steve offers training and consulting services in all aspects of C++ programming and design, including
  - Design Patterns
  - C++ Gotchas
  - Templates and the Standard Template Library
  - Introductory C++
  - Advanced C++
  - Corporate university course licensing, course development, course rejuvenation, and web casting
- See `http://www.semantics.org` for more information.
- Steve also maintains a mailing list for periodic and asynchronous announcements that are likely to be of interest to Steve's clients, readers, and technical adversaries. The message volume is low, and is used to announce upcoming conference talks, magazine articles, courses, web casts, books, and web articles, including his online "Once, Weakly" C++ topic of the week. `http://www.semantics.org/mailinglist.html`.