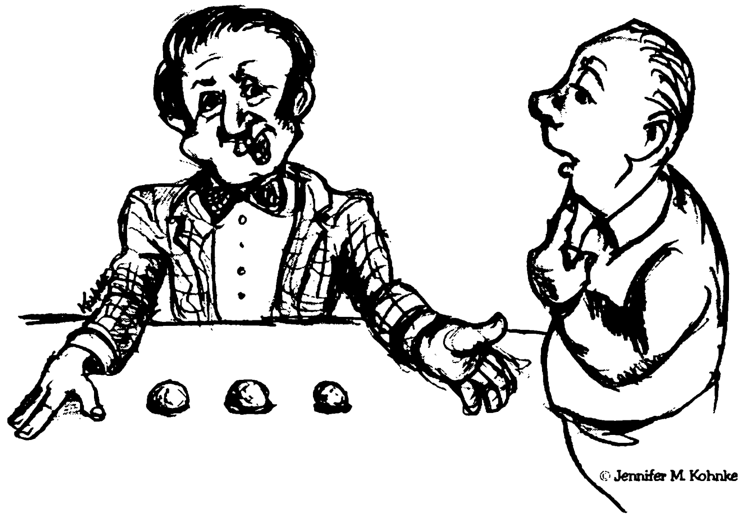
10

LSP: The Liskov Substitution Principle



The primary mechanisms behind the OCP are abstraction and polymorphism. In statically typed languages like C++ and Java, one of the key mechanisms that supports abstraction and polymorphism is inheritance. It is by using inheritance that we can create derived classes that implement abstract methods in base classes.

What are the design rules that govern this particular use of inheritance? What are the characteristics of the best inheritance hierarchies? What are the traps that will cause us to create hierarchies that do not conform to the OCP? These are the questions that are addressed by the Liskov Substitution Principle (LSP).

LSP: The Liskov Substitution Principle

The LSP can be paraphrased as follows:

SUBTYPES MUST BE SUBSTITUTABLE FOR THEIR BASE TYPES.

Barbara Liskov first wrote this principle in 1988.[1] She said,

What is wanted here is something like the following substitution property: If for each object o_1 of type S there is an object o_2 of type T such that for all programs P defined in terms of T, the behavior of P is unchanged when o_1 is substituted for o_2 then S is a subtype of T.

1. [Liskov88].

The importance of this principle becomes obvious when you consider the consequences of violating it. Presume that we have a function *f* that takes, as its argument, a pointer or reference to some base class *B*. Presume also that there is some derivative *D* of *B* which, when passed to *f* in the guise of *B*, causes *f* to misbehave. Then *D* violates the LSP. Clearly *D* is Fragile in the presence of *f*.

The authors of *f* will be tempted to put in some kind of test for *D* so that *f* can behave properly when a *D* is passed to it. This test violates the OCP because now *f* is not closed to all the various derivatives of *B*. Such tests are a code smell that are the result of inexperienced developers (or, what's worse, developers in a hurry) reacting to LSP violations.

A Simple Example of a Violation of the LSP

Violating the LSP often results in the use of Run-Time Type Information (RTTI) in a manner that grossly violates the OCP. Frequently, an explicit `if` statement or `if/else` chain is used to determine the type of an object so that the behavior appropriate to that type can be selected. Consider Listing 10-1.

Listing 10-1

A violation of LSP causing a violation of OCP.

```
struct Point {double x,y;};

struct Shape {
  enum ShapeType {square, circle} itsType;
  Shape(ShapeType t) : itsType(t) {}
};

struct Circle : public Shape
{
  Circle() : Shape(circle) {};
  void Draw() const;
  Point itsCenter;
  double itsRadius;
};

struct Square : public Shape
{
  Square() : Shape(square) {};
  void Draw() const;
  Point itsTopLeft;
  double itsSide;
};

void DrawShape(const Shape& s)
{
  if (s.itsType == Shape::square)
    static_cast<const Square&>(s).Draw();
  else if (s.itsType == Shape::circle)
    static_cast<const Circle&>(s).Draw();
}
```

Clearly, the `DrawShape` function in Listing 10-1 violates the OCP. It must know about every possible derivative of the `Shape` class, and it must be changed whenever new derivatives of `Shape` are created. Indeed, many rightly view the structure of this function as anathema to good design. What would drive a programmer to write a function like this?

Consider Joe the Engineer. Joe has studied object-oriented technology and has come to the conclusion that the overhead of polymorphism is too high to pay.[2] Therefore, he defined class `Shape` without any virtual functions. The classes (structs) `Square` and `Circle` derive from `Shape` and have `Draw()` functions, but they don't override a function in `Shape`. Since `Circle` and `Square` are not substitutable for `Shape`, `DrawShape` must inspect its incoming `Shape`, determine its type, and then call the appropriate `Draw` function.

The fact that `Square` and `Circle` cannot be substituted for `Shape` is a violation of the LSP. This violation forced the violation of the OCP by `DrawShape`. Thus, *a violation of LSP is a latent violation of OCP.*

Square and Rectangle, a More Subtle Violation

Of course, there are other, far more subtle, ways of violating the LSP. Consider an application which uses the `Rectangle` class as described in Listing 10-2.

Listing 10-2

`Rectangle class`

```
class Rectangle
{
  public:
    void   SetWidth(double w)   {itsWidth=w;}
    void   SetHeight(double h)  {itsHeight=w;}
    double GetHeight() const    {return itsHeight;}
    double GetWidth() const     {return itsWidth;}
  private:
    Point  itsTopLeft;
    double itsWidth;
    double itsHeight;
};
```

Imagine that this application works well and is installed in many sites. As is the case with all successful software, its users demand changes from time to time. One day, the users demand the ability to manipulate *squares* in addition to rectangles.

It is often said that inheritance is the *IS-A* relationship. In other words, if a new kind of object can be said to fulfill the IS-A relationship with an old kind of object, then the class of the new object should be derived from the class of the old object.

For all normal intents and purposes, a square *is a* rectangle. Thus, it is logical to view the `Square` class as being derived from the `Rectangle` class. (See Figure 10-1.)

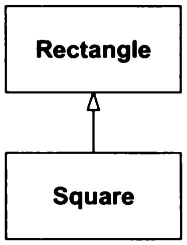


Figure 10-1 Square inherits from Rectangle

This use of the IS-A relationship is sometimes thought to be one of the fundamental techniques of object-oriented analysis:[3] A square is a rectangle, and so the `Square` class should be derived from the `Rectangle` class.

2. On a reasonably fast machine, that overhead is on the order of 1ns per method invocation, so it's hard to see Joe's point.

3. A term that is frequently used but seldom defined.

However, this kind of thinking can lead to some subtle, yet significant, problems. Generally, these problem are not foreseen until we see them in code.

Our first clue that something has gone wrong might be the fact that a `Square` does not need both `itsHeight` and `itsWidth` member variables. Yet it will inherit them from `Rectangle`. Clearly, this is wasteful. In many cases, such waste is insignificant. But if we must create hundreds of thousands of `Square` objects (e.g., a CAD/CAE program in which every pin of every component of a complex circuit is drawn as a square), this waste could be significant.

Let's assume, for the moment, that we are not very concerned with memory efficiency. There are other problems that ensue from deriving `Square` from `Rectangle`. `Square` will inherit the `SetWidth` and `SetHeight` functions. These functions are inappropriate for a `Square`, since the width and height of a square are identical. This is a strong indication that there is a problem. However, there is a way to sidestep the problem. We could override `SetWidth` and `SetHeight` as follows:

```
void Square::SetWidth(double w)
{
  Rectangle::SetWidth(w);
  Rectangle::SetHeight(w);
}

void Square::SetHeight(double h)
{
  Rectangle::SetHeight(h);
  Rectangle::SetWidth(h);
}
```

Now, when someone sets the width of a `Square` object, its height will change correspondingly. And when someone sets the height, its width will change with it. Thus, the invariants[4] of the `Square` remain intact. The `Square` object will remain a mathematically proper square.

```
Square s;
s.SetWidth(1); // Fortunately sets the height to 1 too.
s.SetHeight(2); // sets width and height to 2. Good thing.
```

But consider the following function:

```
void f(Rectangle& r)
{
  r.SetWidth(32); // calls Rectangle::SetWidth
}
```

If we pass a reference to a `Square` object into this function, the `Square` object will be corrupted because the height won't be changed. This is a clear violation of LSP. The `f` function does not work for derivatives of its arguments. The reason for the failure is that `SetWidth` and `SetHeight` were not declared `virtual` in `Rectangle`; therefore, they are not polymorphic.

We can fix this easily. However, when the creation of a derived class causes us to make changes to the base class, it often implies that the design is faulty. Certainly it violates the OCP. We might counter this by saying that forgetting to make `SetWidth` and `SetHeight` `virtual` was the real design flaw, and we are just fixing it now. However, this is hard to justify since setting the height and width of a rectangle are exceedingly primitive operations. By what reasoning would we make them `virtual` if we did not anticipate the existence of `Square`.

4. Those properties that must always be true regardless of state.

Still, let's assume that we accept the argument and fix the classes. We wind up with the code in Listing 10-3.

Listing 10-3

Rectangle and Square that are Self-Consistent.

```
class Rectangle
{
  public:
    virtual void SetWidth(double w)   {itsWidth=w;}
    virtual void SetHeight(double h) {itsHeight=h;}
    double       GetHeight() const   {return itsHeight;}
    double       GetWidth() const    {return itsWidth;}
  private:
    Point  itsTopLeft
    double itsHeight;
    double itsWidth;
};

class Square : public Rectangle
{
  public:
    virtual void SetWidth(double w);
    virtual void SetHeight(double h);
};

void Square::SetWidth(double w)
{
  Rectangle::SetWidth(w);
  Rectangle::SetHeight(w);
}

void Square::SetHeight(double h)
{
  Rectangle::SetHeight(h);
  Rectangle::SetWidth(h);
}
```

The Real Problem

`Square` and `Rectangle` now appear to work. No matter what you do to a `Square` object, it will remain consistent with a mathematical square. And regardless of what you do to a `Rectangle` object, it will remain a mathematical rectangle. Moreover, you can pass a `Square` into a function that accepts a pointer or reference to a `Rectangle`, and the `Square` will still act like a square and will remain consistent.

Thus, we might conclude that the design is now self-consistent and correct. However, this conclusion would be amiss. A design that is self-consistent is not necessarily consistent with all its users! Consider the following function `g`:

```
void g(Rectangle& r)
{
  r.SetWidth(5);
  r.SetHeight(4);
  assert(r.Area() == 20);
}
```

This function invokes the `SetWidth` and `SetHeight` members of what it believes to be a `Rectangle`. The function works just fine for a `Rectangle`, but it declares an assertion error if passed a `Square`. So here is the real problem: *The author of* `g` *assumed that changing the width of a* `Rectangle` *leaves its height unchanged.*

Clearly, it is reasonable to assume that changing the width of a rectangle does not affect its height! However, not all objects that can be passed as `Rectangles` satisfy that assumption. If you pass an instance of a `Square` to a function like `g`, whose author made that assumption, then that function will malfunction. Function `g` is Fragile with respect to the `Square/Rectangle` hierarchy.

Function `g` shows that there exist functions that take pointers or references to `Rectangle` objects, but that cannot operate properly on `Square` objects. Since, for these functions, `Square` is not substitutable for `Rectangle`, the relationship between `Square` and `Rectangle` violates the LSP.

One might contend that the problem lay in function `g`—that the author had no right to make the assumption that width and height were independent. The author of `g` would disagree. The function `g` takes a `Rectagle` as its argument. There are invariants, statements of truth, that obviously apply to a class named `Rectangle`, and one of those invariants is that height and width are independent. The author of `g` had every right to assert this invariant. It is the author of `Square` that has violated the invariant.

Interestingly enough, the author of `Square` did not violate an invariant of `Square`. By deriving `Square` from `Rectangle`, the author of `Square` violated an invariant of `Rectangle`!

Validity Is Not Intrinsic

The LSP leads us to a very important conclusion: *A model, viewed in isolation, cannot be meaningfully validated.* The validity of a model can only be expressed in terms of its clients. For example, when we examined the final version of the `Square` and `Rectangle` classes in isolation, we found that they were self-consistent and valid. Yet when we looked at them from the viewpoint of a programmer who made reasonable assumptions about the base class, the model broke down.

When considering whether a particular design is appropriate or not, one cannot simply view the solution in isolation. One must view it in terms of the reasonable assumptions made by the users of that design.[5]

Who knows what reasonable assumptions the users of a design are going to make? Most such assumptions are not easy to anticipate. Indeed, if we tried to anticipate them all, we'd likely wind up imbuing our system with the smell of Needless Complexity. Therefore, like all other principles, it is often best to defer all but the most obvious LSP violations until the related Fragility has been smelled.

ISA Is about Behavior

So what happened? Why did the apparently reasonable model of the `Square` and `Rectangle` go bad? After all, isn't a `Square` a `Rectangle`? Doesn't the IS-A relationship hold?

Not as far as the author of `g` is concerned! A square might be a rectangle, but from `g`'s point of view, a `Square` object is definitely *not* a `Rectangle` object. Why? Because the *behavior* of a `Square` object is not consistent with `g`'s expectation of the behavior of a `Rectangle` object. Behaviorally, a `Square` is not a `Rectangle`, and it is *behavior* that software is really all about. The LSP makes it clear that in OOD, the IS-A relationship pertains to *behavior* that can be reasonably assumed and that clients depend on.

5. Often you will find that those reasonable assumptions are asserted in the unit tests written for the base class. Yet another good reason to practice test-driven development.

Design by Contract

Many developers may feel uncomfortable with the notion of behavior that is "reasonably assumed." How do you know what your clients will really expect? There is a technique for making those reasonable assumptions explicit, thereby enforcing the LSP. The technique is called design by contract (DBC) and is expounded by Bertrand Meyer.[6]

Using DBC, the author of a class explicitly states the contract for that class. The contract informs the author of any client code about the behaviors that can be relied on. The contract is specified by declaring preconditions and postconditions for each method. The preconditions must be true in order for the method to execute. On completion, the method guarantees that the postconditions are true.

We can view the postcondition of `Rectangle::SetWidth(double w)` as follows:

```
assert((itsWidth == w) && (itsHeight == old.itsHeight));
```

In this example, `old` is the value of the `Rectangle` before `SetWidth` is called. Now the rule for preconditions and postconditions of derivatives, as stated by Meyer, is:

A routine redeclaration [in a derivative] may only replace the original precondition by one equal or weaker, and the original postcondition by one equal or stronger.[7]

In other words, when using an object through its base-class interface, the user knows only the preconditions and postconditions of the base class. Thus, derived objects must not expect such users to obey preconditions that are stronger than those required by the base class. That is, they must accept anything that the base class could accept. Also, derived classes must conform to all the postconditions of the base. That is, their behaviors and outputs must not violate any of the constraints established for the base class. Users of the base class must not be confused by the output of the derived class.

Clearly, the postcondition of `Square::SetWidth(double w)` is weaker[8] than the postcondition of `Rectangle::SetWidth(double w)`, since it does not enforce the constraint, `(itsHeight == old.itsHeight)`. Thus, `the SetWidth method of Square` violates the contract of the base class.

Certain languages, like Eiffel, have direct support for preconditions and postconditions. You can declare them and have the runtime system verify them for you. Neither C++ nor Java has such a feature. In these languages, we must manually consider the preconditions and postcondition of each method and make sure that Meyer's rule is not violated. Moreover, it can be very helpful to document these preconditions and postconditions in the comments for each method.

Specifying Contracts in Unit Tests

Contracts can also be specified by writing unit tests. By thoroughly testing the behavior of a class, the unit tests make the behavior of the class clear. Authors of client code will want to review the unit tests so that they know what to reasonably assume about the classes they are using.

A Real Example

Enough of squares and rectangles! Does the LSP have a bearing on real software? Let's look at a case study that comes from a project that I worked on a few years ago.

6. [Meyer97], Chapter 11, p. 331.
7. [Meyer97], p. 573, Assertion Redeclaration rule (1).
8. The term "weaker" can be confusing. X is weaker than Y if X does not enforce all the constraints of Y. It does not matter how many new constraints X enforces.

Motivation

In the early 1990s, I purchased a third-party class library that had some container classes. The containers were roughly related to the `Bags` and `Sets` of Smalltalk. There were two varieties of `Set` and two similar varieties of `Bag`. The first variety was called "bounded" and was based on an array. The second was called "unbounded" and was based on a linked list.

The constructor for `BoundedSet` specified the maximum number of elements the set could hold. The space for these elements was preallocated as an array within the `BoundedSet`. Thus, if the creation of the `BoundedSet` succeeded, we could be sure that it had enough memory. Since it was based on an array, it was very fast. There were no memory allocations performed during normal operation. And since the memory was preallocated, we could be sure that operating the `BoundedSet` would not exhaust the heap. On the other hand, it was wasteful of memory since it would seldom completely utilize all the space that it had preallocated.

`UnboundedSet`, on the other hand, had no declared limit on the number of elements it could hold. So long as there was heap memory avaliable, the `UnboundedSet` would continue to accept elements. Therefore, it was very flexible. It was also economical in that it only used the memory necessary to hold the elements that it currently contained. It was also slow because it had to allocate and deallocate memory as part of its normal operation. Finally, there was a danger that its normal operation could exhaust the heap.

I was unhappy with the interfaces of these third-party classes. I did not want my application code to be dependent on them because I felt that I would want to replace them with better classes later. Thus, I wrapped the third-party containers in my own abstract interface as shown in Figure 10-2.

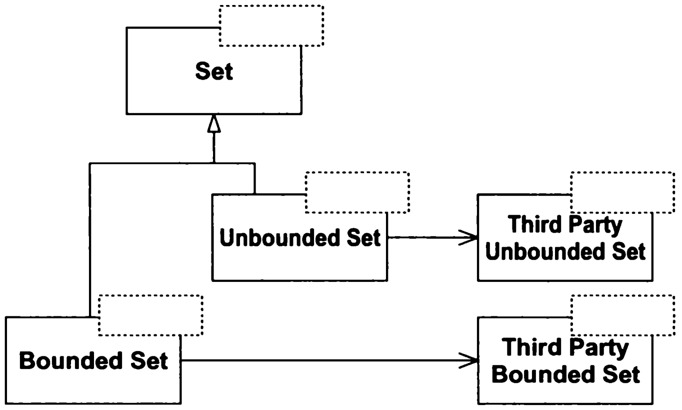


Figure 10-2 Container class adapter layer

I created an abstract class called `Set` that presented pure virtual `Add`, `Delete`, and `IsMember` functions, as shown in Listing 10-4. This structure unified the unbounded and bounded varieties of the two third-party sets and allowed them to be accessed through a common interface. Thus, some client could accept an argument of type `Set<T>&` and would not care whether the actual `Set` it worked on was of the `bounded` or `unbounded` variety. (See the `PrintSet` function in Listing 10-5.)

Listing 10-4
Abstract Set Class

```
template <class T>
class Set
{
  public:
    virtual void Add(const T&) = 0;
    virtual void Delete(const T&) = 0;
    virtual bool IsMember(const T&) const = 0;
};
```

Listing 10-5

PrintSet

```
template <class T>
void PrintSet(const Set<T>& s)
{
  for (Iterator<T>i(s); i; i++
    cout << (*i) << endl;
}
```

It is a big advantage not to have to know or care what kind of `Set` you are using. It means that the programmer can decide which kind of `Set` is needed in each particular instance, and none of the client functions will be affected by that decision. The programmer may choose an `UnboundedSet` when memory is tight and speed is not critical, or the programmer may choose an `BoundedSet` when memory is plentiful and speed is critical. The client functions will manipulate these objects through the interface of the base class `Set` and will therefore not know or care which kind of `Set` they are using.

Problem

I wanted to add a `PersistentSet` to this hierarchy. A persistent set is a set that can be written out to a stream and then read back in later, possibly by a different application. Unfortunately, the only third-party container that I had access to, that also offered persistence, was not a `template` class. Instead, it accepted objects that were derived from the abstract base class `PersistentObject`. I created the hierarchy shown in Figure 10-3.

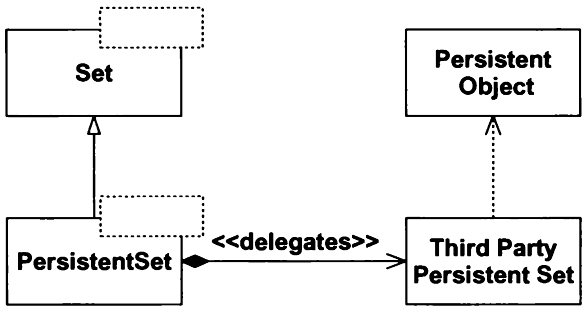


Figure 10-3 Persistent Set Hierarchy

Note that `PersistentSet` contains an instance of the third-party persistent set, to which it delegates all its methods. Thus, if you call `Add` on the `PersistentSet`, it simply delegates that to the appropriate method of the contained third-party persistent set.

On the surface of it, this might look all right. However, there is an ugly implication. Elements that are added to the third-party persistent set must be derived from `PersistentObject`. Since `PersistentSet` simply delegates to the third-party persistent set, any element added to `PersistentSet` must therefore derive from `PersistentObject`. Yet the interface of `Set` has no such constraint.

When a client is adding members to the base class `Set`, that client cannot be sure whether or not the `Set` might actually be a `PersistentSet`. Thus, the client has no way of knowing whether or not the elements it adds ought to be derived from `PersistentObject`.

Consider the code for `PersistentSet::Add()` in Listing 10-6.

Listing 10-6

```
template <typename T>
void PersistentSet::Add(const T& t)
{
  PersistentObject& p =
    dynamic_cast<PersistentObject&>(t);
  itsThirdPartyPersistentSet.Add(p);
}
```

This code makes it clear that if any client tries to add an object that is not derived from the class `PersistentObject` to my `PersistentSet`, a runtime error will ensue. The `dynamic_cast` will throw `bad_cast`. None of the existing clients of the abstract base class `Set` expects exceptions to be thrown on `Add`. Since these functions will be confused by a derivative of `Set`, this change to the hierarchy violates the LSP.

Is this a problem? Certainly. Functions that never before failed when passed a derivative of `Set` may now cause runtime errors when passed a `PersistentSet`. Debugging this kind of problem is relatively difficult since the runtime error occurs very far away from the actual logic flaw. The logic flaw is either the decision to pass a `PersistentSet` into a function or it is the decision to add an object to the `PersistentSet` that is not derived from `PersistentObject`. In either case, the actual decision might be millions of instructions away from the actual invocation of the `Add` method. Finding it can be a bear. Fixing it can be worse.

A Solution That Does *Not* Conform to the LSP

How do we solve this problem? Several years ago, I solved it by convention. Which is to say that I did not solve it in source code. Rather, I established a convention whereby `PersistentSet` and `PersistentObject` were not known to the application as a whole. They were only known to one particular module. This module was responsible for reading and writing all the containers to and from the persistent store. When a container needed to be written, its contents were copied into appropriate derivatives of `PersistentObject` and then added to `PersistentSets`, which were then saved on a stream. When a container needed to be read from a stream, the process was inverted. A `PersistentSet` was read from the stream, and then the `PersistentObjects` were removed from the `PersistentSet` and copied into regular (nonpersistent) objects, which were then added to a regular `Set`.

This solution may seem overly restrictive, but it was the only way I could think of to prevent `PersistentSet` objects from appearing at the interface of functions that would want to add nonpersistent objects to them. Moreover, it broke the dependency of the rest of the application on the whole notion of persistence.

Did this solution work? Not really. The convention was violated in several parts of the application by developers who did not understand the necessity for it. That is the problem with conventions—they have to be continually resold to each developer. If the developer has not learned the convention, or does not agree with it, then the convention will be violated. And one violation can compromise the whole structure.

An LSP-Compliant Solution

How would I solve this now? I would acknowledge that a `PersistentSet` does not have an IS-A relationship with `Set`, that it is not a proper derivative of `Set`. Thus, I would separate the hierarchies, but not completely. There are features that `Set` and `PersistentSet` have in common. In fact, it is only the `Add` method that causes the difficulty with LSP. Consequently, I would create a hierarchy in which both `Set` and `PersistentSet` were siblings beneath an abstract interface that allowed for membership testing, iteration, etc. (See Figure 10-4.) This would allow `PersistentSet` objects to be iterated and tested for membership, etc. But it would not afford the ability to add objects that were not derived from `PersistentObject` to a `PersistentSet`.

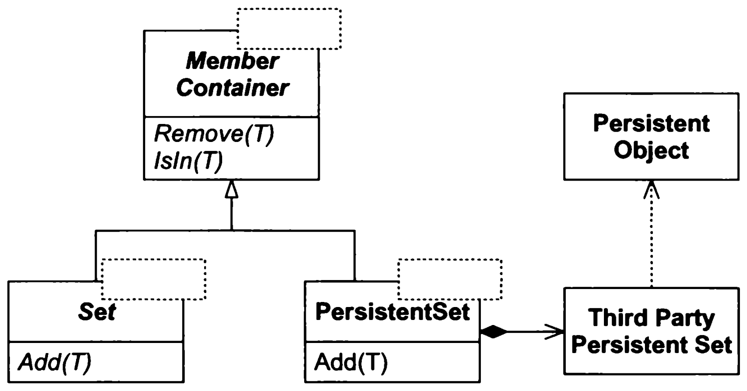


Figure 10-4 A solution that is LSP compliant

Factoring instead of Deriving

Another interesting and puzzling case of inheritance is the case of the `Line` and the `LineSegment`.[9] Consider Listings 10-7 and 10-8. These two classes appear, at first, to be natural candidates for public inheritance. `LineSegment` needs every member variable and every member function declared in `Line`. Moreover, `LineSegment` adds a new member function of its own, `GetLength`, and overrides the meaning of the `IsOn` function. Yet these two classes violate the LSP in a subtle way.

Listing 10-7

`geometry/line.h`

```
#ifndef GEOMETRY_LINE_H
#define GEOMETRY_LINE_H
#include "geometry/point.h"

class Line
{
  public:
    Line(const Point& p1, const Point& p2);

    double       GetSlope()         const;
    double       GetIntercept()     const; // Y Intercept
    Point        GetP1()            const {return itsP1;};
    Point        GetP2()            const {return itsP2;};
    virtual bool IsOn(const Point&) const;

  private:
    Point itsP1;
    Point itsP2;
};
#endif
```

Listing 10-8

`geometry/lineseg.h`

```
#ifndef GEOMETRY_LINESEGMENT_H
#define GEOMETRY_LINESEGMENT_H
class LineSegment : public Line
```

9. Despite the similarity that this example has to the Square/Rectangle example, it comes from a real application and was subject to the real problems discussed.

```
{
  public:
    LineSegment(const Point& p1, const Point& p2);
    double       GetLength()       const;
    virtual bool IsOn(const Point&) const;
};
#endif
```

A user of `Line` has a right to expect that all points that are colinear with it are on it. For example, the point returned by the `Intercept` function is the point at which the line intersects the y-axis. Since this point is collinear with the line, users of `Line` have a right to expect that `IsOn(Intercept()) == true`. In many instances of `LineSegment`, however, this statement will fail.

Why is this an important issue? Why not simply derive `LineSegment` from `Line` and live with the subtle problems? This is a judgment call. There are *rare* occasions when it is more expedient to accept a subtle flaw in polymorphic behavior than to attempt to manipulate the design into complete LSP compliance. Accepting compromise instead of pursuing perfection is an engineering trade-off. A good engineer learns when compromise is more *profitable* than perfection. However, conformance to the LSP *should not be surrendered lightly.* The guarantee that a subclass will always work where its base classes are used is a powerful way to manage complexity. Once it is forsaken, we must consider each subclass individually.

In the case of the `Line` and `LineSegment`, there is a simple solution that illustrates an important tool of OOD. If we have access to both the `Line` and `LineSegment` classes, then we can *factor* the common elements of both into an abstract base class. Listings 10-9 through 10-11 show the factoring of `Line` and `LineSegment` into the base class `LinearObject`.

Listing 10-9

`geometry/linearobj.h`

```
#ifndef GEOMETRY_LINEAR_OBJECT_H
#define GEOMETRY_LINEAR_OBJECT_H

#include "geometry/point.h"

class LinearObject
{
  public:
    LinearObject(const Point& p1, const Point& p2);

    double   GetSlope() const;
    double   GetIntercept() const;

    Point GetP1() const {return itsP1;};
    Point GetP2() const {return itsP2;};
    virtual int   IsOn(const Point&) const = 0; // abstract.

  private:
    Point itsP1;
    Point itsP2;
};
#endif
```

Listing 10-10

geometry/line.h

```
#ifndef GEOMETRY_LINE_H
#define GEOMETRY_LINE_H
#include "geometry/linearobj.h"

class Line : public LinearObject
{
  public:
    Line(const Point& p1, const Point& p2);
    virtual bool IsOn(const Point&) const;
};
#endif
```

Listing 10-11

geometry/lineseg.h

```
#ifndef GEOMETRY_LINESEGMENT_H
#define GEOMETRY_LINESEGMENT_H
#include "geometry/linearobj.h"

class LineSegment : public LinearObject
{
  public:
    LineSegment(const Point& p1, const Point& p2);

    double       GetLength()       const;
    virtual bool IsOn(const Point&) const;
};
#endif
```

`LinearObject` represents both `Line` and `LineSegment`. It provides most of the functionality and data members for both subclasses, with the exception of the `IsOn` method, which is pure virtual. Users of `LinearObject` are not allowed to assume that they understand the extent of the object they are using. Thus, they can accept either a `Line` or a `LineSegment` with no problem. Moreover, users of `Line` will never have to deal with a `LineSegment`.

Factoring is a design tool that is best applied before there is much code written. Certainly, if there were dozens of clients of the `Line` class shown in Listing 10-7, we would not have had an easy time of factoring out the `LinearObject` class. When factoring is possible, however, it is a powerful tool. If qualities can be factored out of two subclasses, there is the distinct possibility that other classes will show up later that need those qualities, too. Of factoring, Rebecca Wirfs–Brock, Brian Wilkerson, and Lauren Wiener say:

> *We can state that if a set of classes all support a common responsibility, they should inherit that responsibility from a common superclass.*
> *If a common superclass does not already exist, create one, and move the common responsibilities to it. After all, such a class is demonstrably useful—you have already shown that the responsibilities will be inherited by some classes. Isn't it conceivable that a later extension of your system might add a new subclass that will support those same responsibilities in a new way? This new superclass will probably be an abstract class.*[10]

10. [WirfsBrock90], p. 113.

Listing 10-12 shows how the attributes of `LinearObject` can be used by an unanticipated class, `Ray`. A `Ray` is substitutable for a `LinearObject`, and no user of `LinearObject` would have any trouble dealing with it.

Listing 10-12

geometry/ray.h

```
#ifndef GEOMETRY_RAY_H
#define GEOMETRY_RAY_H

class Ray : public LinearObject
{
  public:
    Ray(const Point& p1, const Point& p2);
    virtual bool IsOn(const Point&) const;
};
#endif
```

Heuristics and Conventions

There are some simple heuristics that can give you some clues about LSP violations. They all have to do with derivative classes that somehow *remove* functionality from their base classes. A derivative that does less than its base is usually not substitutable for that base, and therefore violates the LSP.

Degenerate Functions in Derivatives

Consider Listing 10-13. The `f` function in `Base` is implemented. However, in `Derived` it is degenerate. Presumably, the author of `Derived` found that function `f` had no useful purpose in a `Derived`. Unfortunately, the users of `Base` don't know that they shouldn't call `f`, so there is a substitution violation.

Listing 10-13

A degenerate function in a derivative

```
public class Base
{
  public void f() {/*some code*/}
}

public class Derived extends Base
{
  public void f() {}
}
```

The presence of degenerate functions in derivatives is not always indicative of an LSP violation, but it's worth looking at them when they occur.

Throwing Exceptions from Derivatives

Another form of violation is the addition of exceptions to methods of derived classes whose bases don't throw them. If the users of the base classes don't expect exceptions, then adding them to the methods of derivatives is not substitutable. Either the expectations of the users must be altered or the derived classes should not throw the exceptions.

Conclusion

The OCP is at the heart of many of the claims made for OOD. When this principle is in effect, applications are more maintainable, reusable, and robust. The LSP is one of the prime enablers of the OCP. It is the substitutability of subtypes that allows a module, expressed in terms of a base type, to be extensible without modification. That substitutability must be something that developers can depend on implicitly. Thus, the contract of the base type has to be well and prominently understood, if not explicitly enforced, by the code.

The term "IS-A" is too broad to act as a definition of a subtype. The true definition of a subtype is "substitutable," where substitutability is defined by either an explicit or implicit contract.

Bibliography

1. Meyer, Bertrand. *Object-Oriented Software Construction*, 2d ed. Upper Saddle River, NJ: Prentice Hall, 1997.
2. Wirfs–Brock, Rebecca, et al. *Designing Object-Oriented Software*. Englewood Cliffs, NJ: Prentice Hall, 1990.
3. Liskov, Barbara. Data Abstraction and Hierarchy. *SIGPLAN Notices*, 23,5 (May 1988).

11

DIP: The Dependency-Inversion Principle

Nevermore
Let the great interests of the State depend
Upon the thousand chances that may sway
A piece of human frailty

—Sir Thomas Noon Talfourd (1795–1854)

DIP: The Dependency-Inversion Principle

a. High-level modules should not depend on low-level modules. Both should depend on abstractions.
b. Abstractions should not depend on details. Details should depend on abstractions.

Over the years, many have questioned why I use the word "inversion" in the name of this principle. It is because more traditional software development methods, such as Structured Analysis and Design, tend to create software structures in which high-level modules depend on low-level modules, and in which policy depends on detail. Indeed one of the goals of these methods is to define the subprogram hierarchy that describes how the high-level modules make calls to the low-level modules. The initial design of the `Copy` program in Figure 7-1 on page 90 is a good example of such a hierarchy. The dependency structure of a well-designed, object-oriented program is "inverted" with respect to the dependency structure that normally results from traditional procedural methods.

Consider the implications of high-level modules that depend on low-level modules. It is the high-level modules that contain the important policy decisions and business models of an application. These modules contain the identity of the application. Yet, when these modules depend on the lower level modules, changes to the lower level modules can have direct effects on the higher level modules and can force them to change in turn.

This predicament is absurd! It is the high-level, policy-setting modules that ought to be influencing the low-level, detailed modules. The modules that contain the high-level business rules should take precedence over, and be independent of, the modules that contain the implementation details. High-level modules simply should not depend on low-level modules in any way.

Moreover, it is high-level, policy-setting modules that we want to be able to reuse. We are already quite good at reusing low-level modules in the form of subroutine libraries. When high-level modules depend on low-level modules, it becomes very difficult to reuse those high-level modules in different contexts. However, when the high-level modules are independent of the low-level modules, then the high-level modules can be reused quite simply. This principle is at the very heart of framework design.

Layering

According to Booch, "...all well-structured object-oriented architectures have clearly defined layers, with each layer providing some coherent set of services though a well-defined and controlled interface."[1] A naive interpretation of this statement might lead a designer to produce a structure similar to Figure 11-1. In this diagram, the high-level `Policy` layer uses a lower-level `Mechanism` layer, which in turn uses a detailed-level `Utility` layer. While this may look appropriate, it has the insidious characteristic that the `Policy` layer is sensitive to changes all the way down in the `Utility` layer. *Dependency is transitive.* The `Policy` layer depends on something that depends on the `Utility` layer; thus, the `Policy` layer transitively depends on the `Utility` layer. This is very unfortunate.

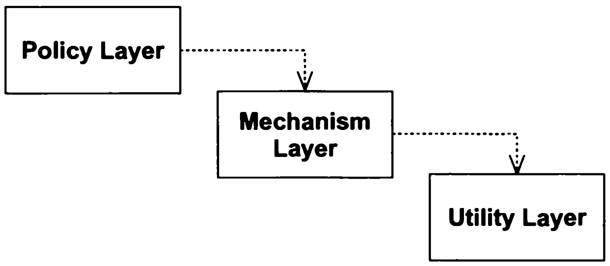


Figure 11-1 Naive layering scheme

Figure 11-2 shows a more appropriate model. Each of the upper-level layers declares an abstract interface for the services that it needs. The lower-level layers are then realized from these abstract interfaces. Each higher-level class uses the next-lowest layer through the abstract interface. Thus, the upper layers do not depend on the lower layers. Instead, the lower layers depend on abstract service interfaces *declared in* the upper layers. Not only is the transitive dependency of `PolicyLayer` on `UtilityLayer` broken, but even the direct dependency of the `PolicyLayer` on `MechanismLayer` is broken.

An Inversion of Ownership

Notice that the inversion here is not just one of dependencies, it is also one of interface ownership. We often think of utility libraries as owning their own interfaces. But when the DIP is applied, we find that the clients tend to own the abstract interfaces and that their servers derive from them.

1. [Booch96], p. 54.

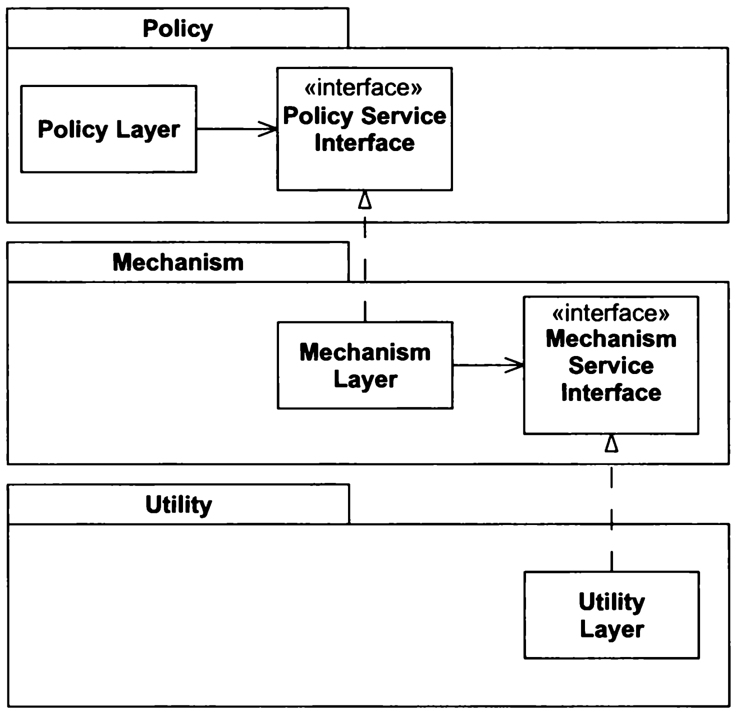


Figure 11-2 Inverted Layers

This is sometimes known as the Hollywood principle: "Don't call us, we'll call you."[2] The lower-level modules provide the implementation for interfaces that are declared within, and called by, the upper-level modules.

Using this inversion of ownership, `PolicyLayer` is unaffected by any changes to `MechanismLayer` or `UtilityLayer`. Moreover, `PolicyLayer` can be reused in any context that defines lower-level modules that conform to the `PolicyServiceInterface`. Thus, by inverting the dependencies, we have created a structure, which is simultaneously more flexible, durable, and mobile.

Depend On Abstractions

A somewhat more naive, yet still very powerful, interpretation of the DIP is the simple heuristic: "Depend on abstractions." Simply stated, this heuristic recommends that you should not depend on a concrete class—that all relationships in a program should terminate on an abstract class or an interface.

According to this heuristic,

- No variable should hold a pointer or reference to a concrete class.
- No class should derive from a concrete class.
- No method should override an implemented method of any of its base classes.

Certainly this heuristic is usually violated at least once in every program. Somebody has to create the instances of the concrete classes, and whatever module does that will depend on them.[3] Moreover, there seems no reason to follow this heuristic for classes that are concrete but nonvolatile. If a concrete class is not going to change very much, and no other similar derivatives are going to be created, then it does very little harm to depend on it.

2. [Sweet85].

3. Actually, there are ways around this if you can use strings to create classes. Java allows this. So do several other languages. In such languages, the names of the concrete classes can be passed into the program as configuration data.

For example, in most systems the class that describes a string is concrete. In Java, for example, it is the concrete class `String`. This class is not volatile. That is, it does not change very often. Therefore it does no harm to depend directly on it.

However, most concrete classes that *we* write as part of an application program are volatile. It is *those* concrete classes that we do not want to depend directly on. Their volatility can be isolated by keeping them behind an abstract interface.

This is not a complete solution. There are times when the interface of a volatile class must change, and this change must be propagated to the abstract interface that represents the class. Such changes break through the isolation of the abstract interface.

This is the reason that the heuristic is a bit naive. If, on the other hand, we take the longer view that the client classes declare the service interfaces that they need, then the only time the interface will change is when the *client* needs the change. Changes to the classes that implement the abstract interface will not affect the client.

A Simple Example

Dependency inversion can be applied wherever one class sends a message to another. For example, consider the case of the `Button` object and the `Lamp` object.

The `Button` object senses the external environment. On receiving the `Poll` message, it determines whether or not a user has "pressed" it. It doesn't matter what the sensing mechanism is. It could be a button icon on a GUI, a physical button being pressed by a human finger, or even a motion detector in a home security system. The `Button` object detects that a user has either activated or deactivated it.

The `Lamp` object affects the external environment. On receiving a `TurnOn` message, it illuminates a light of some kind. On receiving a `TurnOff` message, it extinguishes that light. The physical mechanism is unimportant. It could be an LED on a computer console, a mercury vapor lamp in a parking lot, or even the laser in a laser printer.

How can we design a system such that the `Button` object controls the `Lamp` object? Figure 11-3 shows a naive design. The `Button` object receives `Poll` messages, determines if the button has been pressed, and then simply sends the `TurnOn` or `TurnOff` message to the `Lamp`.

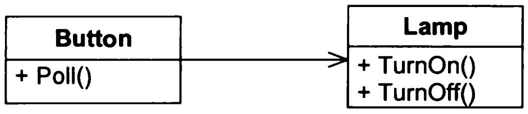


Figure 11-3 Naive Model of a Button and a Lamp

Why is this naive? Consider the Java code that is implied by this model (Listing 11-1). Note that the `Button` class depends directly on the `Lamp` class. This dependency implies that `Button` will be affected by changes to `Lamp`. Moreover, it will not be possible to reuse `Button` to control a `Motor` object. In this design, `Button` objects control `Lamp` objects, and *only* `Lamp` objects.

Listing 11-1

`Button.java`

```
public class Button
{
  private Lamp itsLamp;
  public void poll()
  {
    if (/*some condition*/)
      itsLamp.turnOn();
  }
}
```

This solution violates the DIP. The high-level policy of the application has not been separated from the low-level implementation. The abstractions have not been separated from the details. Without such a separation, the high-level policy automatically depends on the low-level modules, and the abstractions automatically depend on the details.

Finding the Underlying Abstraction

What is the high-level policy? It is the abstraction that underlies the application, the truths that do not vary when the details are changed. It is the system *inside* the system—it is the metaphor. In the `Button/Lamp` example, the underlying abstraction is to detect an on/off gesture from a user and relay that gesture to a target object. What mechanism is used to detect the user gesture? Irrelevant! What is the target object? Irrelevant! These are details that do not impact the abstraction.

The design in Figure 11-3 can be improved by inverting the dependency on the `Lamp` object. In Figure 11-4, we see that the `Button` now holds an association to something called a `ButtonServer`. `ButtonServer` provides abstract methods that `Button` can use to turn something on or off. `Lamp` implements the `ButtonServer` interface. Thus, `Lamp` is now doing the depending, rather than being depended on.

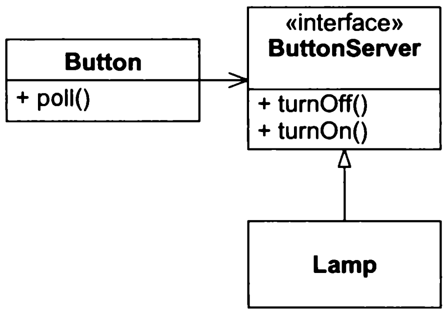


Figure 11-4 Dependency Inversion Applied to the Lamp

The design in Figure 11-4 allows a `Button` to control any device that is willing to implement the `ButtonServer` interface. This gives us a great deal of flexibility. It also means that `Button` objects will be able to control objects that have not yet been invented.

However, this solution also puts a constraint on any object that needs to be controlled by a `Button`. Such an object *must* implement the `ButtonServer` interface. This is unfortunate because these objects may also want to be controlled by a `Switch` object or some object other than a `Button`.

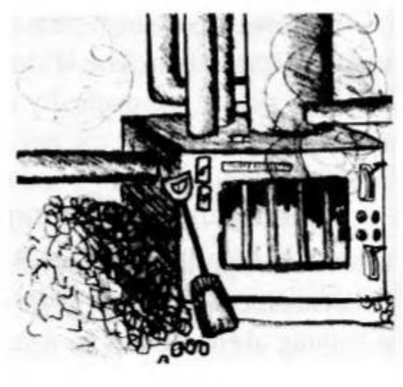
By inverting the direction of the dependency and making the `Lamp` do the depending instead of being depended on, we have made `Lamp` depend on a different detail—`Button`. Or have we?

`Lamp` certainly depends on `ButtonServer`, but `ButtonServer` does not depend on `Button`. Any kind of object that knows how to manipulate the `ButtonServer` interface will be able to control a `Lamp`. Thus, the dependency is in name only. And we can fix that by changing the name of `ButtonServer` to something a bit more generic like `SwitchableDevice`. We can also ensure that `Button` and `SwitchableDevice` are kept in separate libraries, so that the use of `SwitchableDevice` does not imply the use of `Button`.

In this case, nobody owns the interface. We have the interesting situation where the interface can be used by lots of different clients and implemented by lots of different servers. Thus, the interface needs to stand alone without belonging to either group. In C++, we would put it in a separate namespace and library. In Java we would put it in a separate package.[4]

4. In dynamic languages like Smalltalk, Pyrhon, or Ruby, the interface simply wouldn't exist as an explicit source-code entity.

The Furnace Example



Let's look at a more interesting example. Consider the software that might control the regulator of a furnace. The software can read the current temperature from an IO channel and instruct the furnace to turn on or off by sending commands to a different IO channel. The structure of the algorithm might look something like Listing 11-2.

Listing 11-2
Simple algorithm for a thermostat

```
#define TERMOMETER 0x86
#define FURNACE    0x87
#define ENGAGE     1
#define DISENGAGE  0

void Regulate(double minTemp, double maxTemp)
{
  for(;;)
  {
    while (in(THERMOMETER) > minTemp)
      wait(1);
    out(FURNACE,ENGAGE);

    while (in(THERMOMETER) < maxTemp)
      wait(1);
    out(FURNACE,DISENGAGE);
  }
}
```

The high-level intent of the algorithm is clear, but the code is cluttered with lots of low-level details. This code could never be reused with different control hardware.

This may not be much of a loss since the code is very small. But even so, it is a shame to have the algorithm lost for reuse. We'd rather invert the dependencies and see something like Figure 11-5.

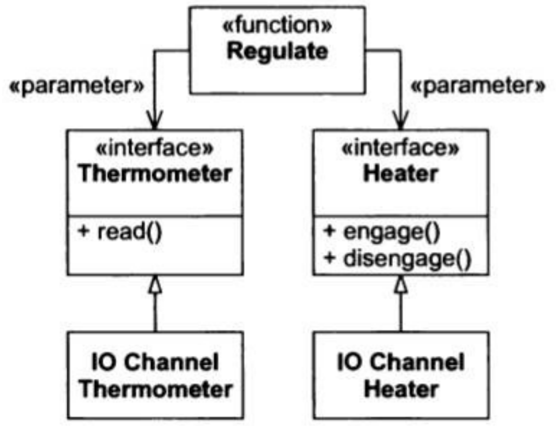


Figure 11-5 Generic Regulator

This shows that the regulate function takes two arguments that are both interfaces. The `Thermometer` interface can be read, and the `Heater` interface can be engaged and disengaged. This is all the `Regulate` algorithm needs. Now it can be written as shown in Listing 11-3.

Listing 11-3

Generic Regulator

```
void Regulate(Thermometer& t, Heater& h,
              double minTemp, double maxTemp)
{
  for(;;)
  {
    while (t.Read() > minTemp)
      wait(1);
    h.Engage();

    while (t.Read() < maxTemp)
      wait(1);
    h.Disengage();
  }
}
```

This has inverted the dependencies such that the high-level regulation policy does not depend on any of the specific details of the thermometer or the furnace. The algorithm is nicely reusable.

Dynamic v. Static Polymorphism

We have achieved the inversion of the dependencies, and made `Regulate` generic, through the use of dynamic polymorphism (i.e., abstract classes or interfaces). However, there is another way. We could have used the static form of polymorphism afforded by C++ templates. Consider Listing 11-4.

Listing 11-4

```
template <typename THERMOMETER, typename HEATER>
class Regulate(THERMOMETER& t, HEATER& h,
              double minTemp, double maxTemp)
{
  for(;;)
  {
    while (t.Read() > minTemp)
      wait(1);
    h.Engage();

    while (t.Read() < maxTemp)
      wait(1);
    h.Disengage();
  }
}
```

This achieves the same inversion of dependencies without the overhead (or flexibility) of dynamic polymorphism. In C++, the `Read`, `Engage`, and `Disengage` methods could all be nonvirtual. Moreover, any class that declares these methods can be used by the template. They do not have to inherit from a common base.

As a template, `Regulate` does not depend on any particular implementation of these functions. All that is required is that the class substituted for `HEATER` have an `Engage` and a `Disengage` method and that the class substituted for `THERMOMETER` have a `Read` function. Thus, those classes must implement the interface defined by the template. In other words, both `Regulate`, and the classes that `Regulate` uses, must agree on the same interface, and they both depend on that agreement.

Static polymorphism breaks the source-code dependency nicely, but it does not solve as many problems as does dynamic polymorphism. The disadvantages of the template approach are (1) The types of HEATER and THERMOMETER cannot be changed at runtime; and (2) The use of a new kind of HEATER or THERMOMETER will force recompilation and redeployment. So unless you have an extremely stringent requirement for speed, dynamic polymorphism should be preferred.

Conclusion

Traditional procedural programming creates a dependency structure in which policy depends on detail. This is unfortunate since the policies are then vulnerable to changes in the details. Object-oriented programming inverts that dependency structure such that both details and policies depend on abstraction, and service interfaces are often owned by their clients.

Indeed, it is this inversion of dependencies that is the hallmark of good object-oriented design. It doesn't matter what language a program is written in. If its dependencies are inverted, it has an OO design. If its dependencies are not inverted, it has a procedural design.

The principle of dependency inversion is the fundamental low-level mechanism behind many of the benefits claimed for object-oriented technology. Its proper application is necessary for the creation of reusable frameworks. It is also critically important for the construction of code that is resilient to change. Since the abstractions and details are all isolated from each other, the code is much easier to maintain.

Bibliography

1. Booch, Grady. *Object Solutions*. Menlo Park, CA: Addison–Wesley, 1996.
2. Gamma, et al. *Design Patterns*. Reading, MA: Addison–Wesley, 1995.
3. Sweet. Richard E. The Mesa Programming Environment. *SIGPLAN Notices*, 20(7) (July 1985): 216–229.

12

ISP: The Interface-Segregation Principle

This principle deals with the disadvantages of "fat" interfaces. Classes that have "fat" interfaces are classes whose interfaces are not cohesive. In other words, the interfaces of the class can be broken up into groups of methods. Each group serves a different set of clients. Thus, some clients use one group of member functions, and other clients use the other groups.

The ISP acknowledges that there are objects that require noncohesive interfaces; however, it suggests that clients should not know about them as a single class. Instead, clients should know about abstract base classes that have cohesive interfaces.

Interface Pollution

Consider a security system. In this system, there are `Door` objects that can be locked and unlocked, and which know whether they are open or closed. (See Listing 12-1.)

Listing 12-1

```
Security Door
class Door
{
  public:
    virtual void Lock()   = 0;
    virtual void Unlock() = 0;
    virtual bool IsDoorOpen() = 0;
};
```

This class is abstract so that clients can use objects that conform to the `Door` interface, without having to depend on particular implementations of `Door`.

Now consider that one such implementation, `TimedDoor`, needs to sound an alarm when the door has been left open for too long. In order to do this, the `TimedDoor` object communicates with another object called a `Timer`. (See Listing 12-2.)

Listing 12-2

```
class Timer
{
  public:
    void Register(int timeout, TimerClient* client);
};

class TimerClient
{
  public:
    virtual void TimeOut() = 0;
};
```

When an object wishes to be informed about a time-out, it calls the `Register` function of the `Timer`. The arguments of this function are the time of the time-out, and a pointer to a `TimerClient` object whose `TimeOut` function will be called when the time-out expires.

How can we get the `TimerClient` class to communicate with the `TimedDoor` class so that the code in the `TimedDoor` can be notified of the time-out? There are several alternatives. Figure 12-1 shows a naive solution. We force `Door`, and therefore `TimedDoor`, to inherit from `TimerClient`. This ensures that `TimerClient` can register itself with the `Timer` and receive the `TimeOut` message.

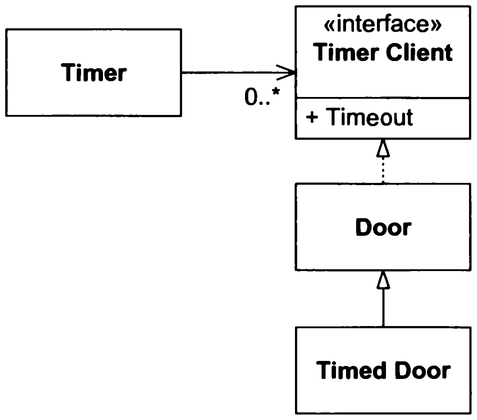


Figure 12-1 Timer Client at Top of Hierarchy

Although this solution is common, it is not without problems. Chief among these is that the `Door` class now depends on `TimerClient`. Not all varieties of `Door` need timing. Indeed, the original `Door` abstraction had nothing whatever to do with timing. If timing-free derivatives of `Door` are created, those derivatives will have to provide degenerate implementations for the `TimeOut` method—a potential violation of the LSP. Moreover, the applications that use those derivatives will have to import the definition of the `TimerClient` class, even though it is not used. That smells of Needless Complexity and Needless Redundancy.

This is an example of interface pollution, a syndrome that is common in statically typed languages like C++ and Java. The interface of `Door` has been polluted with a method that it does not require. It has been forced to incorporate this method solely for the benefit of one of its subclasses. If this practice is pursued, then every time a derivative needs a new method, that method will be added to the base class. This will further pollute the interface of the base class, making it "fat."

Moreover, each time a new method is added to the base class, that method must be implemented (or allowed to default) in derived classes. Indeed, an associated practice is to add these interfaces to the base class giving them degenerate implementations, specifically so that derived classes are not burdened with the need to implement them. As we learned previously, such a practice can violate the LSP, leading to maintenance and reusability problems.

Separate Clients Mean Separate Interfaces

Door and TimerClient represent interfaces that are used by completely different clients. Timer uses TimerClient, and classes that manipulate doors use Door. Since the clients are separate, the interfaces should remain separate, too. Why? Because clients exert forces on the interfaces they use.

The Backwards Force Applied by Clients On Interfaces

When we think of forces that cause changes in software, we normally think about how changes to interfaces will affect their users. For example, we would be concerned about the changes to all the users of TimerClient if the TimerClient interface changed. However, there is a force that operates in the other direction. Sometimes it is the *user* that forces a change to the interface.

For example, some users of Timer will register more than one time-out request. Consider the TimedDoor. When it detects that the Door has been opened, it sends the Register message to the Timer, requesting a time-out. However, before that time-out expires, the door closes, remains closed for a while, and then opens again. This causes us to register a *new* time-out request before the old one has expired. Finally, the first time-out request expires and the TimeOut function of the TimedDoor is invoked. The Door alarms falsely.

We can correct this situation by using the convention shown in Listing 12-3. We include a unique timeOutId code in each time-out registration, and we repeat that code in the TimeOut call to the TimerClient. This allows each derivative of TimerClient to know which time-out request is being responded to.

Listing 12-3

```
Timer with ID
class Timer
{
  public:
    void Register(int timeout,
                  int timeOutId,
                  TimerClient* client);
};

class TimerClient
{
  public:
    virtual void TimeOut(int timeOutId) = 0;
};
```

Clearly this change will affect all the users of TimerClient. We accept this since the lack of the timeOutId is an oversight that needs correction. However, the design in Figure 12-1 will also cause Door, and all clients of Door to be affected by this fix! This smells of Rigidity and Viscosity. Why should a bug in TimerClient have *any* affect on clients of Door derivatives that do not require timing? When a change in one part of the program affects other completely unrelated parts of the program, the cost and repercussions of changes become unpredictable, and the risk of fallout from the change increases dramatically.

ISP: The Interface-Segregation Principle

Clients should not be forced to depend on methods that they do not use.

When clients are forced to depend on methods that they don't use, then those clients are subject to changes to those methods. This results in an inadvertent coupling between all the clients. Said another way, when a client depends on a class that contains methods that the client does not use, but that other clients *do* use, then that client will be affected by the changes that those other clients force upon the class. We would like to avoid such couplings where possible, and so we want to separate the interfaces.

Class Interfaces v. Object Interfaces

Consider the `TimedDoor` again. Here is an object which has two separate interfaces used by two separate clients—`Timer` and the users of `Door`. These two interfaces *must* be implemented in the same object, since the implementation of both interfaces manipulates the same data. So how can we conform to the ISP? How can we separate the interfaces when they must remain together?

The answer to this lies in the fact that clients of an object do not need to access it through the interface of the object. Rather, they can access it through delegation or through a base class of the object.

Separation through Delegation

One solution is to create an object that derives from `TimerClient` and delegates to the `TimedDoor`. Figure 12-2 shows this solution.

When the `TimedDoor` wants to register a time-out request with the `Timer`, it creates a `DoorTimerAdapter` and registers it with the `Timer`. When the `Timer` sends the `TimeOut` message to the `DoorTimerAdapter`, the `DoorTimerAdapter` delegates the message back to the `TimedDoor`.

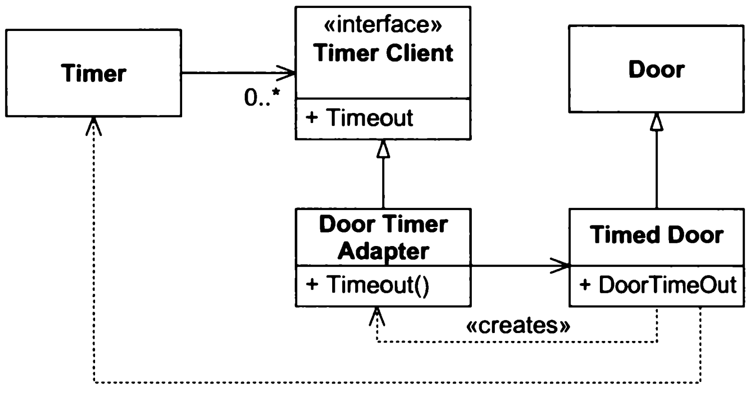


Figure 12-2 Door Timer Adapter

This solution conforms to the ISP and prevents the coupling of `Door` clients to `Timer`. Even if the change to `Timer` shown in Listing 12-3 were to be made, none of the users of `Door` would be affected. Moreover, `TimedDoor` does not have to have the exact same interface as `TimerClient`. The `DoorTimerAdapter` can *translate* the `TimerClient` interface into the `TimedDoor` interface. Thus, this is a very general purpose solution. (See Listing 12-4.)

Listing 12-4
TimedDoor.cpp

```
class TimedDoor : public Door
{
  public:
    virtual void DoorTimeOut(int timeOutId);
};

class DoorTimerAdapter : public TimerClient
{
  public:
    DoorTimerAdapter(TimedDoor& theDoor)
    : itsTimedDoor(theDoor)
    {}

    virtual void TimeOut(int timeOutId)
    {itsTimedDoor.DoorTimeOut(timeOutId);}

  private:
    TimedDoor& itsTimedDoor;
};
```

However, this solution is also somewhat inelegant. It involves the creation of a new object every time we wish to register a time-out. Moreover, the delegation requires a very small, but still nonzero, amount of runtime and memory. There are application domains, such as embedded real-time control systems, in which runtime and memory are scarce enough to make this a concern.

Separation through Multiple Inheritance

Figure 12-3 and Listing 12-5 show how multiple inheritance can be used to achieve the ISP. In this model, `TimedDoor` inherits from both `Door` and `TimerClient`. Although clients of both base classes can make use of `TimedDoor`, neither actually depends on the `TimedDoor` class. Thus, they use the same object through separate interfaces.

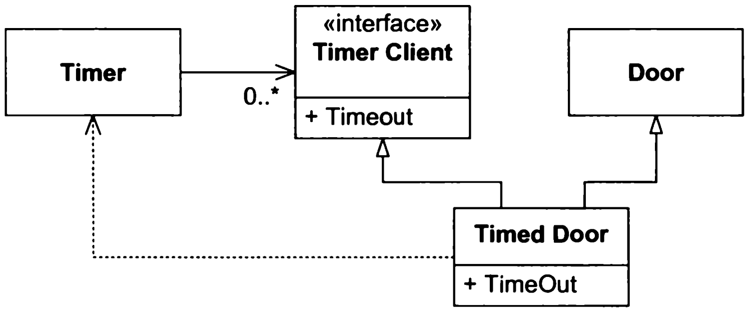


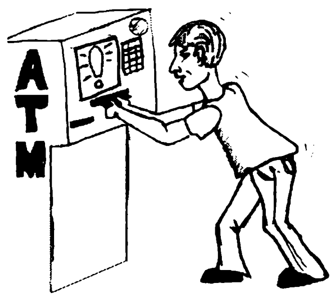
Figure 12-3 Multiply inherited Timed Door

Listing 12-5
`TimedDoor.cpp`

```
class TimedDoor : public Door, public TimerClient
{
  public:
    virtual void TimeOut(int timeOutId);
};
```

This solution is my normal preference. The only time I would choose the solution in Figure12-2 over Figure 12-3 is if the translation performed by the `DoorTimerAdapter` object were necessary, or if different translations were needed at different times.

The ATM User Interface Example



Now let's consider a slightly more significant example. The traditional automated teller machine (ATM) problem. The user interface of an ATM machine needs to be very flexible. The output may need to be translated into many different languages. It may need to be presented on a screen, or on a braille tablet, or spoken out a speech synthesizer. Clearly this can be achieved by creating an abstract base class that has abstract methods for all the different messages that need to be presented by the interface.

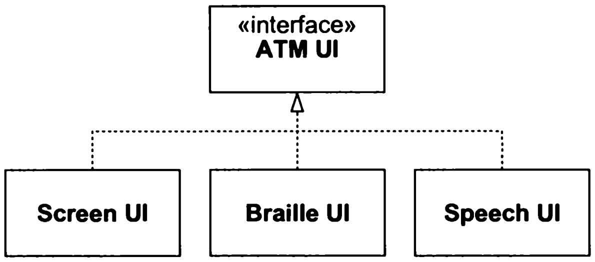


Figure 12-4

Consider also that each different transaction that the ATM can perform is encapsulated as a derivative of the class `Transaction`. Thus, we might have classes such as `DepositTransaction`, `WithdrawalTransaction`, and `TransferTransaction`. Each class invokes methods of the `UI`. For example, in order to ask the user to enter the amount he wishes to deposit, the `DepositTransaction` object invokes the `RequestDepositAmount` method of the `UI` class. Likewise, in order to ask the user how much money he wants to transfer between accounts, the `TransferTransaction` object calls the `RequestTransferAmount` method of `UI`. This corresponds to the diagram in Figure 12-5.

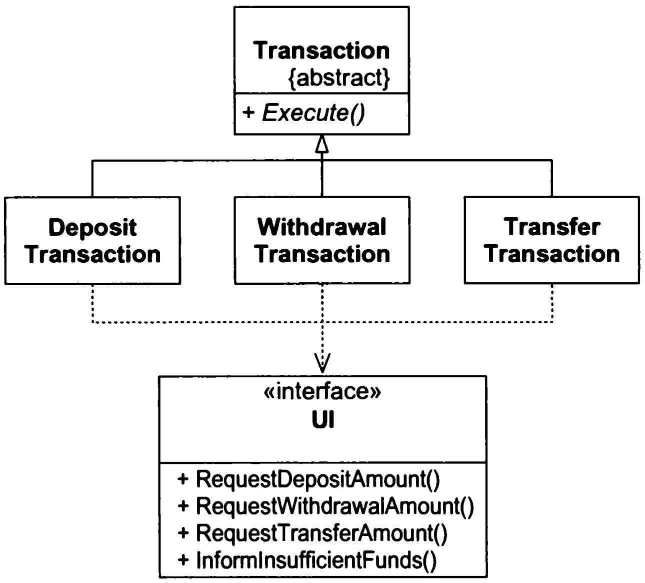


Figure 12-5 ATM Transaction Hierarchy

Notice that this is precisely the situation that the ISP tells us to avoid. Each transaction is using methods of the UI that no other class uses. This creates the possibility that changes to one of the derivatives of `Transaction` will force corresponding change to the UI, thereby affecting all the other derivatives of `Transaction` and every other class that depends on the `UI` interface. Something smells like Rigidity and Fragility around here.

For example, if we were to add a `PayGasBillTransaction`, we would have to add new methods to UI in order to deal with the unique messages that this transaction would want to display. Unfortunately, since `DepositTransaction`, `WithdrawalTransaction`, and `TransferTransaction` all depend on the `UI` interface, they must all be recompiled. Worse, if the transactions were all deployed as components in separate DLLs or shared libraries, then those components would have to be redeployed, even though none of their logic was changed. Can you smell the Viscosity?

This unfortunate coupling can be avoided by segregating the `UI` interface into individual interfaces such as `DepositUI`, `WithdrawUI`, and `TransferUI`. These separate interfaces can then be multiply inherited into the final `UI` interface. Figure 12-6 and Listing 12-6 show this model.

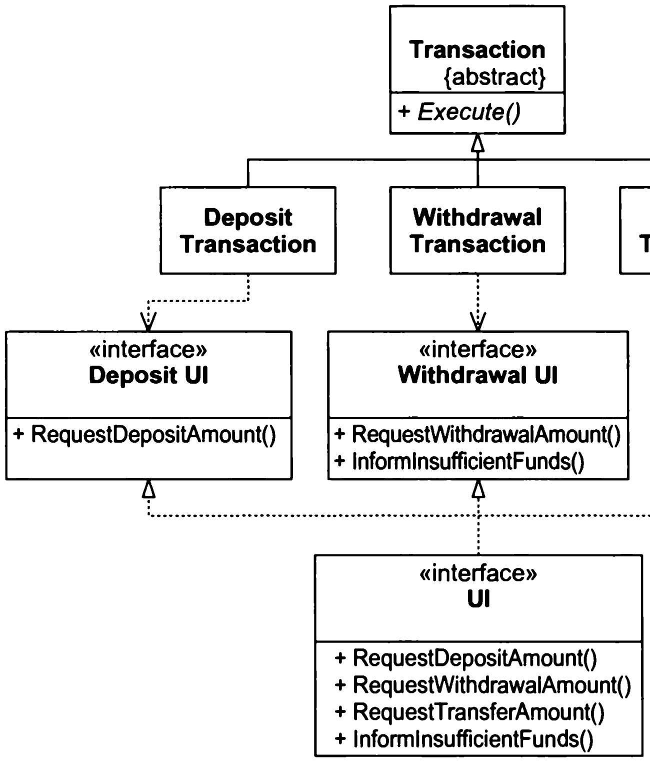


Figure 12-6 Segregated ATM UI Interface

Whenever a new derivative of the `Transaction` class is created, a corresponding base class for the abstract `UI` interface will be needed, and so the `UI` interface and all its derivatives must change. However, these classes are not widely used. Indeed, they are probably only used by `main` or whatever process boots the system and creates the concrete `UI` instance. So the impact of adding new `UI` base classes is minimized.

Listing 12-6
Segregated ATM UI Interface

```
class DepositUI
{
  public:
    virtual void RequestDepositAmount() = 0;
};

class DepositTransaction : public Transaction
{
  public:
    DepositTransaction(DepositUI& ui)
    : itsDepositUI(ui)
    {}

    virtual void Execute()
    {
      ...
      itsDepositUI.RequestDepositAmount();
      ...
    }
  private:
    DepositUI& itsDepositUI;
};

class WithdrawalUI
{
  public:
    virtual void RequestWithdrawalAmount() = 0;
};

class WithdrawalTransaction : public Transaction
{
  public:
    WithdrawalTransaction(WithdrawalUI& ui)
    : itsWithdrawalUI(ui)
    {}

    virtual void Execute()
    {
      ...
      itsWithdrawalUI.RequestWithdrawalAmount();
      ...
    }
  private:
    WithdrawalUI& itsWithdrawalUI;
};

class TransferUI
{
  public:
    virtual void RequestTransferAmount() = 0;
};

class TransferTransaction : public Transaction
{
  public:
    TransferTransaction(TransferUI& ui)
    : itsTransferUI(ui)
    {}

    virtual void Execute()
    {
      ...
      itsTransferUI.RequestTransferAmount();
      ...
    }
  private:
    TransferUI& itsTransferUI;
};

class UI : public DepositUI
         , public WithdrawalUI
         , public TransferUI
```

```
{
  public:
    virtual void RequestDepositAmount();
    virtual void RequestWithdrawalAmount();
    virtual void RequestTransferAmount();
};
```

A careful examination of Listing 12-6 will show one of the issues with ISP conformance that was not obvious from the `TimedDoor` example. Note that each transaction must somehow know about its particular version of the `UI`. `DepositTransaction` must know about `DepositUI`, `WithdrawTransaction` must know about `WithdrawUI`, etc. In Listing 12-6, I have addressed this issue by forcing each transaction to be constructed with a reference to its particular UI. Note that this allows me to employ the idiom in Listing 12-7.

Listing 12-7

Interface Initialization Idiom

```
UI Gui; // global object;

void f()
{
    DepositTransaction dt(Gui);
}
```

This is handy, but it also forces each transaction to contain a reference member to its UI. Another way to address this issue is to create a set of global constants as shown in Listing 12-8. Global variables are not always a symptom of a poor design. In this case they provide the distinct advantage of easy access. Since they are references, it is impossible to change them in any way. Therefore they cannot be manipulated in a way that would surprise other users.

Listing 12-8

Seperate Global Pointers

```
// in some module that gets linked in
// to the rest of the app.

static UI Lui; // non-global object;
DepositUI&    GdepositUI    = Lui;
WithdrawalUI& GwithdrawalUI = Lui;
TransferUI&   GtransferUI   = Lui;

// In the depositTransaction.h module

class WithdrawalTransaction : public Transaction
{
  public:

    virtual void Execute()
    {
      ...
      GwithdrawalUI.RequestWithdrawalAmount();
      ...
    }
};
```

In C++, one might be tempted to put all the globals in Listing 12-8 into a single class in order to prevent pollution of the global namespace. Listing 12-9 shows such an approach. This, however, has an unfortunate effect. In order to use `UIGlobals`, you must `#include ui_globals.h`. This, in turn, `#includes depositUI.h`, `withdrawUI.h`, and `transferUI.h`. This means that any module wishing to use any of the UI interfaces transitively depends on all of them— exactly the situation that the ISP warns us to avoid. If a change is made to any of the UI interfaces, all modules that `#include "ui_globals.h"` are forced to recompile. The `UIGlobals` class has recombined the interfaces that we had worked so hard to segregate!

Listing 12-9
Wrapping the Globals in a class

```
// in ui_globals.h

#include "depositUI.h"
#include "withdrawalUI.h"
#include "transferUI.h"

class UIGlobals
{
  public:
    static WithdrawalUI& withdrawal;
    static DepositUI&   deposit;
    static TransferUI&  transfer
};

// in ui_globals.cc

static UI Lui; // non-global object;
DepositUI&    UIGlobals::deposit    = Lui;
WithdrawalUI& UIGlobals::withdrawal = Lui;
TransferUI&   UIGlobals::transfer   = Lui;
```

The Polyad v. the Monad

Consider a function `g` that needs access to both the `DepositUI` and the `TransferUI`. Consider also that we wish to pass the UIs into this function. Should we write the function prototype like this?

```
void g(DepositUI&, TransferUI&);
```

Or should we write it like this?

```
void g(UI&);
```

The temptation to write the latter (monadic) form is strong. After all, we know that in the former (polyadic) form, both arguments will refer to the *same object*. Moreover, if we were to use the polyadic form, its invocation might look like this:

```
g(ui, ui);
```

Somehow, this seems perverse.

Perverse or not, the polyadic form is often preferable to the monadic form. The monadic form forces `g` to depend on every interface included in `UI`. Thus, when `WithdrawUI` changes, `g` and all clients of `g` could be affected. This is more perverse than `g(ui,ui)`! Moreover, we cannot be sure that both arguments of `g` will *always* refer to the same object! In the future, it may be that the interface objects are separated for some reason. The fact that all interfaces are combined into a single object is information that g does not need to know. Thus, I prefer the polyadic form for such functions.

Grouping Clients. Clients can often be grouped together by the service methods they call. Such groupings allow segregated interfaces to be created for each group instead of each client. This greatly reduces the number of interfaces that the service has to implement, and it also prevents the service from depending on each client type.

Sometimes, the methods invoked by different groups of clients will overlap. If the overlap is small, then the interfaces for the groups should remain separate. The common functions should be declared in all the overlapping interfaces. The server class will inherit the common functions from each of those interfaces, but it will implement them only once.

Changing Interfaces. When object-oriented applications are maintained, the interfaces to existing classes and components often change. There are times when these changes have a huge impact and force the recompilation and redeployment of a very large part of the system. This impact can be mitigated by adding new interfaces to existing objects, rather than changing the existing interface. Clients of the old interface that wish to access methods of the new interface can query the object for that interface, as shown in Listing 12-10.

Listing 12-10

```
void Client(Service* s)
{
  if (NewService* ns = dynamic_cast<NewService*>(s))
  {
    // use the new service interface
  }
}
```

As with all principles, care must be taken not to overdo it. The spectre of a class with hundreds of different interfaces, some segregated by client and others segregated by version, would be frightening indeed.

Conclusion

Fat classes cause bizarre and harmful couplings between their clients. When one client forces a change on the fat class, all the other clients are affected. Thus, clients should only have to depend on methods that they actually call. This can be achieved by breaking the interface of the fat class into many client-specific interfaces. Each client-specific interface declares only those functions that its particular client, or client group, invoke. The fat class can then inherit all the client-specific interfaces and implement them. This breaks the dependence of the clients on methods that they don't invoke, and it allows the clients to be independent of each other.

Bibliography

1. Gamma, et al. *Design Patterns*. Reading, MA: Addison–Wesley, 1995.