Chapter 6 Abstraction, Refinement, and Testing

Abstract diagrams are good for many purposes. At the whiteboard, you want to exhibit the main ideas of something without all the details of program code. Perhaps you want to say what it does and not how, or what it requires of other components that plug in to it. And whether it's a single procedure or an entire planetwide distributed system, you want to fit it all on one board and convey useful things about it.

When it comes to documentation, a component description that makes clear the essential vision of your design will help future maintainers understand it quickly. Their short-order updates will more likely cohere with the rest of the design, thereby giving your brilliant ideas a longer life. For users of the component (whether end users or other programmers), you don't want to show how the thing works inside but only what they can do with it.

We have seen how to draw and write these abstract descriptions, but how can you be sure they accurately represent the code? The concepts of abstraction and refinement capture the essential relationship between these descriptions. This chapter is about different forms of abstraction and refinement, and it explains the rules for showing that a more detailed model refines (or conforms to) a more abstract one.

Refinement and conformance are a focal point in a Catalysis design review, in which you check that the design or implementation meets its specification(s).

Testing fits naturally into this approach to abstraction and refinement. This chapter also discusses how to test different kinds of refinement relations, including the one between the implementation of an operation and its specification.

You can read Sections 6.1 and 6.2 on a first pass, which touches all the main points.

6.1 *Zooming In and Out: Why Abstract and Refine?*

A major theme of Catalysis is precise abstraction: the ability to look at a design or a model in only as much detail as necessary and without loss of precision. You can precisely describe your code to your colleagues in documents or in presentations, or just sketching over coffee, without getting into superfluous detail. The abstract views can isolate different concerns; you can present the behavior of a component from the point of view of a particular user (or of another component) omitting details seen by another user (or through another interface). You can restrict yourself to the externally visible behavior, or you can describe the internal design scheme. You can describe only one component, a partial collaboration pattern, or the way the components fit together; or you can describe architectural rules followed by all the components.

The zoomed-out, abstract views and the zoomed-in, detailed views must be clearly related. If you write, "and we use the kwik-kache approach to cache information on the client," the link between this abstract intent and the code must be quite clear for it to survive the first few rounds of maintenance by new programmers.

Enter the refinement relation. Using it, you can tell whether the code for a component conforms to the interface expected by its clients and whether a system, if designed to behave as specified, would contribute to the business needs; you can also link individual requirements to specific features of a design. All this gives you a much better start on what is the real long-term problem: change management.

The degree of rigor of this traceability is variable. In a critical context, you can do these checks in mathematical detail. In more ordinary circumstances, you document the main points of correspondence to guide reviewers and maintainers and use these points as the basis for verification, design reviews, and testing.

Testing of object and component designs can be more difficult than in traditional systems because of the added complication of polymorphism, inheritance, and arbitrary overriding of behaviors. The essential idea of testing is to verify that an implementation meets its specification—the same goal as that of refinement except that testing tackles the problem by monitoring runtime behaviors under a systematically derived set of test cases. This chapter outlines a systematic test approach based on refinement.

© ***abstraction*** (1) A description of something that omits some details that are not relevant to the purpose of the abstraction; the converse of *refinement*. Types, collaborations, and action specs are different kinds of abstractions.

(2) To *abstract* (verb) is to create an abstraction; also called *generalize*, *specify*, and sometimes *analyze*.

© ***refinement*** (1) A detailed description that conforms to another (its abstraction). Everything said about the abstraction holds, perhaps in a somewhat different form, in the refinement. Also called realization.

(2) The relationship between the abstract and detailed descriptions.

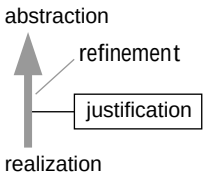
(3) To *refine* (verb) is to create a refinement; also called *design*, *implement*, or *specialize*.

© ***conformance*** One behavioral description conforms to another if (and only if) any object that behaves as described by one also behaves as described by the other (given a mapping between the two descriptions). A *conformance* is a relationship between the two descriptions, accompanied by a *justification* that includes the mapping between them and the rationale for the choices made. Refinement and conformance form the basis of traceability and document the answer to the "why" question: Why is this design done this way?

© ***retrieval*** A function that determines the value of an abstract attribute from the stored implementation data (or otherwise detailed attributes); used with a conformance to show how the attributes map to the abstraction as a prerequisite to showing how the behavior specifications are also met.

© ***implementation*** Program code that conforms to an abstraction; requires no further refinement (strictly speaking, it still goes through compilation and the like).

© ***testing*** The activity of uncovering defects in an implementation by comparing its behavior against that of its specification under a given set of runtime stimuli (the *test cases* or *test data*).



Suppose you ask a hotel for "a room with a nice view, for five people; it should not be noisy in the morning"—an abstract requirement, A. The clerk responds by assigning you "the deluxe penthouse suite overlooking Niagara Falls; its three bedrooms each have two double beds; and it has a built-in Jacuzzi and gym"—a realization, B. B is a *refinement* of A—that is, it *conforms* to A—provided the hotel can *justify* to you that (1) overlooking Niagara Falls constitutes "a nice view"; (2) the humble penthouse suite can suffice as "a room"; (3) the six double beds will serve to accommodate your party of five; (4) the roar of millions of gallons of water will, in fact, be a soothing background whisper; (5) the built-in Jacuzzi and gym do not conflict with anything you've asked for.

6.1.1 Four Basic Kinds of Abstraction and Refinement

Our models center on either the behavior expected of individual objects (large and small) or the designs for how groups of objects collaborate. Each of the primary abstractions—type and collaboration—has two main forms of refinement. Collaboration refinements affect multiple participants in the collaboration; type refinement should not affect a client in any way. Most design steps are a combination of these basic four varieties.

6.1.1.1 Behavior of an Object

We describe an object's behavior using a type, with two parts to its specification: the operation specifications (usually pre- and postconditions) defining what it does; and the static model, providing the vocabulary of terms for the operation specs.

If the type spec and the implementation look different, we need ways of determining whether the code conforms to the type. We treat the two main parts of the type separately, giving us *operation abstraction* and *model abstraction*.

An operation spec (and a static model) is a bit like the usage instructions for a machine (with a simplified drawing of the machine): It tells us what to expect as users. But if we remove the top from the machine, we may see a more complicated mechanism at work. The same thing happens when we look at the implementation code that meets a type spec: Its stored data, variable names, and specific sequences of statements are not seen from the outside.

6.1.1.2 Collaborations among Objects

We describe designs for objects using collaborations—collections of actions. A joint action defines a goal achieved collaboratively between the participant objects, using post-conditions whose vocabulary is the model of each of the participants. Collaborations range from business interactions ("banks trade stocks") to hardware ("fax sender sends document to receiver") to software ("scrollbar displays file position").

An abstract action spec states only the goal achieved and the participants it affects. But we can put more detail into the design by working out a protocol of interactions between the participants. Such refinements might include banks make deals, confirm deals, settle the accounts; fax connects, sends page, confirms, repeats; file notifies scrollbar of change of position.

Similarly, we may discover that each of the participants is itself an abstraction made up of distinct parts that play roles in the collaboration. The banks' traders make the deal, but their back offices do the settlement. Again, the two aspects of the collaboration can be treated separately, giving *action abstraction* and *object abstraction*.

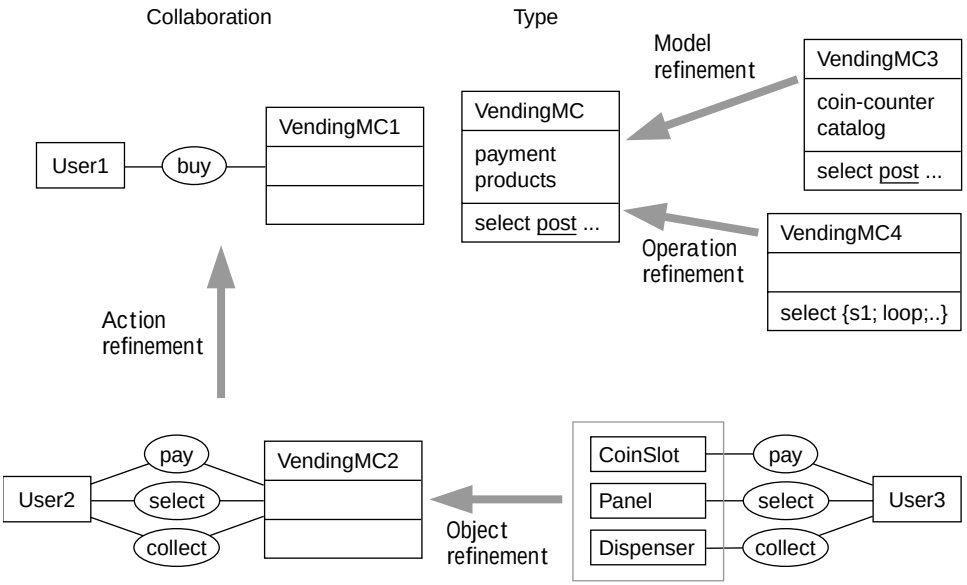


Figure 6.1 Four basic kinds of abstraction and refinement.

The four basic kinds of abstraction and refinement are shown in Figure 6.1. Most abstractions can be understood as combinations of the four basic varieties shown in Table 6.1.

6.1.2 Refinement Trees

Big refinements are made up of smaller ones. A requirements spec and a completely programmed implementation of it may look quite different, but their relationship can be seen as a combination of several smaller refinement steps.

Table 6.1 Basic Varieties of Abstractions

Abstraction	What It Does	Conformance and Justification
Operation	Specifies what an operation achieves in terms of its effect on the object executing it rather than how it works	Does the sequence of statements in code have the specified net effect?
Model	Defines the state of an object (or component) as a smaller and simpler set of attributes than the actual variables or fields used in the design; or simpler than some other model that presents a more detailed view.	How would you compute each abstract attribute from the data stored in the implementation, or from the more detailed attributes?
Action	Describes a complex protocol of interaction between objects as a single action, again characterized by the effect it has on the participants.	What sequences of detailed actions will realize the effect of the abstract action? Use state charts, sequence or activity diagrams.
Object	Treats an entire group of objects (such as a component or subsystem or corporation) as if it were a single one, characterizing its behavior with a type.	How do the constituent objects (and their actions) correspond to the abstract object (and its actions)?

So we can, in theory at least, relate a most abstract specification to the most detailed program code (or business model) through a succession of primitive refinements, each documented by a complete model (see Figure 6.2). If you have a great deal of time to spare, you might try it for a small design! This is what computers are for, of course, and appropriate tools can do a great deal to help. In practice, we use the ideas more informally and use design patterns as ready-made refinement schemes.

We'll now take a brief look at each of the four basic kinds of abstractions. Later sections treat them in more detail, describe how the conformance should be documented, and provide a full example.

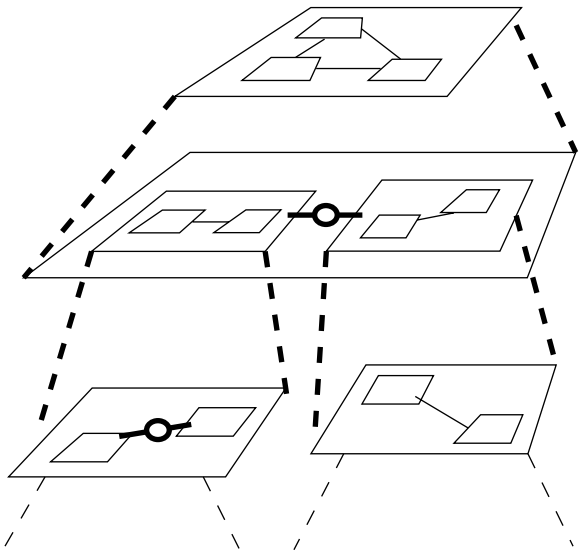


Figure 6.2 Refinements continue recursively.

6.1.3 Operation Abstraction

One of the most basic forms of abstraction is the operation specification: the idea that I can tell you some of the things that are achieved by an operation, omitting the detail of how it works and omitting things it achieves that I don't know or don't care about, such as sequences of algorithmic steps, intermediate states, variables used, and so on. The operation specs we usually encounter are pre- and postconditions, although they may also include rely and guarantee conditions. In a rely condition, the designer assumes the condition will remain undisturbed by anyone else while the operation is executing; a guarantee condition is one that the designer undertakes to maintain true during execution.

Operation specs can be used as the basis of a *test harness*: they can be incorporated into the code in such a way that an exception is raised if any of them ever evaluates to false. (Eiffel supports pre- and postconditions directly; the standard C++ library includes an assert macro.)

```
float square_root (float y);                        // specification
// pre:        y > 0
// post:       abs(return*return – y) < y/1e6              -- almost equal

float square_root (float y)                         // implementation
{
    assert (y > 0);                                 // precondition
    float x= y;
    while (abs(x*x–y)>=y/1e6) { x= (x+y/x)/2; }                 // miracle
    assert (abs (x*x – y) < y/1e6);                 // post: x*x == y (almost)
```

```
        return x;
    }
```

Quality assurance departments like operation specs because, apart from helping to document the code, they act as a definite test harness (see Figure 6.3). In a component-based environment, you frequently plug components together that were not originally designed together; as a result, integration testing becomes a much more frequent activity. Every component (which might mean individual objects or huge subsystems) therefore must come with its own test kit to monitor its behavior when employed in a new configuration.

In Catalysis, we characterize behavior using type definitions, attaching postconditions to the operations. In Java, the corresponding construct is the interface: Classes that implement an interface must provide the listed operations. Wise interface writers append comments specifying what clients expect each operation to do, and classes that claim to implement the interface should conform to those specifications even though each will do so in its own way. In C++, the pure abstract class plays the role of the Java interface in design.

Operation refinement, then, means to write code that conforms to an effects spec, which can be tested by writing the spec in executable form. Operational is the form of abstraction having the longest history, dating back to Turing. Those who crave mathematical certainty that their code conforms to the spec are referred to [Morgan] or [Hoare].

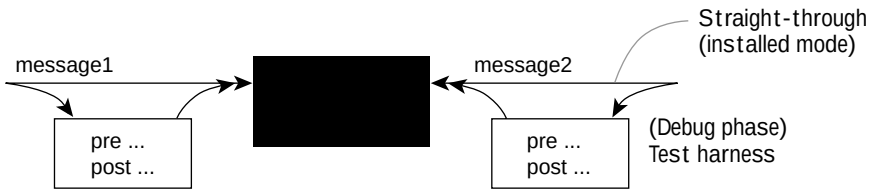


Figure 6.3 Operation specs: in testing versus in production.

6.1.4 Model Abstraction

The postconditions of the operations on an object usually must refer to attributes that help describe the object's state. It's difficult to describe any but the most primitive types without using attributes. We have also seen how we use associations as pictorially presented attributes.

Any implementation will also use internal stored variables operated on by the code of the operations, but they need not be the same as the model attributes used by the postconditions. Model attributes are only a hypothetical means of describing the object's state to help explain its behavior. For example, you might use the concept of its length to help describe operations on a queue (of tasks, orders, and so on), as shown in Figure 6.4.

We can think of several implementations of a Queue, but not all of them will have a length instance variable or method. Nevertheless, it is undeniable that every Queue has a

length. That is what an attribute is about: it is a piece of information about the object and not necessarily a feature of any implementation.

An attribute can always be *retrieved* from an implementation. Suppose I publish the type in Figure 6.4 on the Web and invite tenders for implementation. A hopeful programmer sends me an array implementation:

```
class ArrayQueue implements Queue
{    private Object array [ ] ;              // the list of items
     private int insertionIndex;             // where items are put
     private int extractionIndex;            // where items are gotten from
     public void put (Object x)
     {    array[insertionIndex]= x;
          insertionIndex= (insertionIndex+1) % array.length;
     } ...
```

As a quality assurance exercise, I want to check whether the code of put (say) conforms to my spec. But my spec and this code talk in different vocabularies: It has no length. I need to translate from one model to the other—to map to the abstraction—before I can

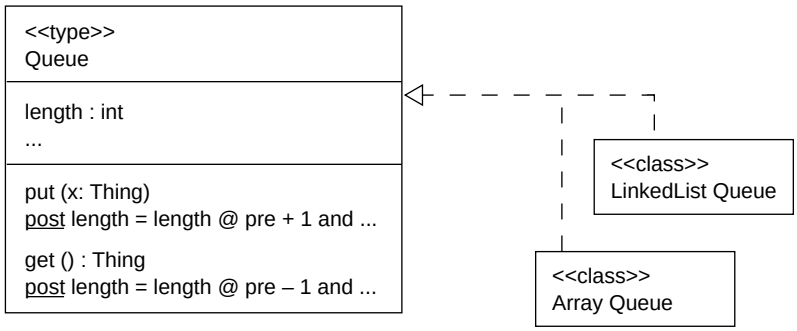


Figure 6.4 Different implementations of the same type model.

begin. So I write back to the programmer and say, "Where's your length?" The answer comes back:

```
private int length ( )
{ return (insertionIndex – extractionIndex) % array.length; }
```

In other words, I have been provided with a function that retrieves or abstracts from the implementation's terms to the spec's. (And, of course, it is read-only: It would be confusing if it changed anything.) Now I can see that the put code indeed increases the length, as I required. If working that out by only inspecting the code is not my style, I can ask that the designer include my pre- and postconditions as assertions in the code so that we can test it properly.

Again, quality assurance chiefs love this stuff. They demand that every implementation be supplied with a set of retrieval functions: that is, read-only abstraction functions for

computing the value of every attribute in the abstract spec. This also applies to associations, which we have previously observed are merely pictorial presentations of attributes.

Another implementation of a queue is based on a linked list. There is not necessarily any variable that corresponds directly to the model's length, but you can retrieve it by counting the nodes.

It doesn't matter whether retrieval functions are slow and inefficient: They are required only for verification either by testing or by reasoning. The exercise of writing them often exposes mistakes in an implementation when the designer realizes that a vital piece of information is missing.

Notice that in Catalysis, we do not expect that attributes and associations will always be publicly supplied for use by clients. There are, of course, many attributes to which it is useful for clients to have "get" and sometimes "set" access; but modelers often use attributes to express intermediate information they don't expect to be available directly to clients.

On a larger scale, more-complex models can be used to represent the types of whole systems or components and are usually shown pictorially. In an abstract model, the attributes and their types are chosen to help specify the operations on the component as a whole and, according to good object-oriented analysis practice, are based on a model of the domain. However, anyone who has been involved in practical OOD is aware that the design phase introduces all sorts of extra classes as patterns are applied to help generalize the design, make it more efficient, distribute the design, provide persistence or a GUI, and so on. But we can still retrieve the abstract model from any true implementation in the same way as for the simpler models.

Model refinement, then, means to establish the relationship between the more abstract model used to define postconditions and the more complex practical implementation. Retrieve functions translate from the refined model attributes to the abstract ones.

Model refinement has the second longest history, dating back to VDM and Z in the 1970s.

6.1.5 Action Abstraction: Messages and Actions

At the programming level, *messages* are the interactions between objects (in most OO programming languages). Some messages have variants on the basic theme, such as synchronous versus asynchronous (waiting or not waiting for the invoked operation to complete). Envisaging complex sequences of messages can be difficult, so we draw sequence diagrams such as the one shown in Figure 6.5.

Sequence diagrams have the disadvantage of being bad for encapsulation, particularly when multiple levels of calls are shown on one diagram. Unfortunately, they allow you to see in one diagram the response to various messages of several objects at once and so encourage you to base the design of one object on the internal mechanisms of the others. They also show only one sequence of events and so make it easy to forget other cases and to forget that each object may receive the same messages in other configurations. However, sequence diagrams make it easy to get an initial grip on a design, so we use them

with caution. It is often good practice to limit the diagram to only one level of nesting and to use postconditions to understand what those events achieve.

The same diagrams can be used to show the interactions between objects in the business world and interactions between large components.

But in any but the most detailed level of design, we usually deal in actions: dialog with an outcome definable with a postcondition but made up of messages we do not care about. For example, I might tell you, "I bought some coffee" rather than expect you to listen to a long tale about how I approached a vending machine, inserted several coins, pressed one of the selector buttons, and so on. The former statement abstracts the latter detailed sequence and includes any other means of achieving the same effects. In Catalysis, actions are characterized principally by their effects; to show how an action is achieved by some combination of smaller ones, you document a refinement.

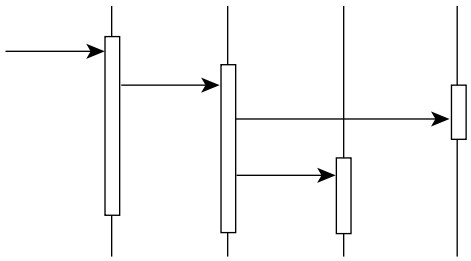


Figure 6.5 Sequences of messages realize abstract actions.

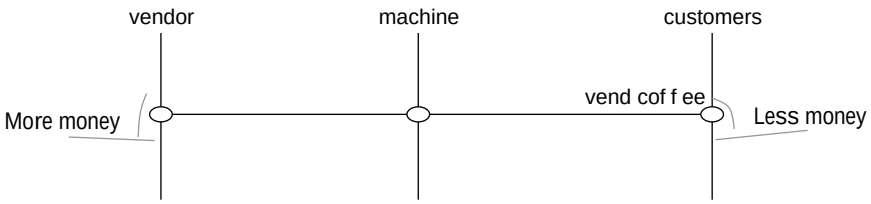


Figure 6.6 Occurrence of a joint action.

A single action may involve several participants, becuase it may abstract several smaller actions that may have different participants. On a Catalysis sequence diagram, the small ellipses mark the participating objects (vertical lines) in each occurrence of an action (horizontal lines). We also mark the states or changes of states of participants (see Figure 6.6).

OO messages in programming languages are only one subtype of actions: those that always have a distinct sender and receiver (see Section 4.2.7, From Joint to Localized Actions).[1] We can use action abstractions to represent interactions external to the software, those between users and software, and those between objects within the software. Within

the software, action abstractions are very useful for abstracting the standard interactions that happen within certain frameworks and patterns, such as observer.

Sequence diagrams illustrate sample occurrences of actions, but an action type can be drawn with the types of its participants and a postcondition written in terms of the participants' attributes (again, whether the types represent software or domain objects), as shown in Figure 6.7. The ability to define the effects even at an abstract level is what makes it worth doing. Abstraction without precision is often just waffle; until some precision is used, it is typically not reliable.

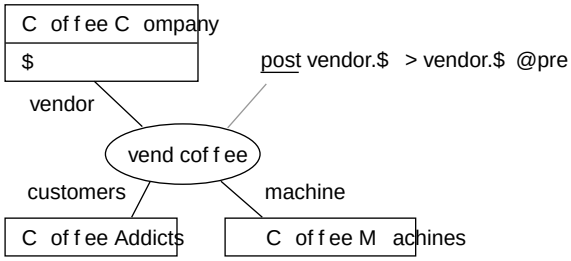


Figure 6.7 Action type shown on a collaboration.

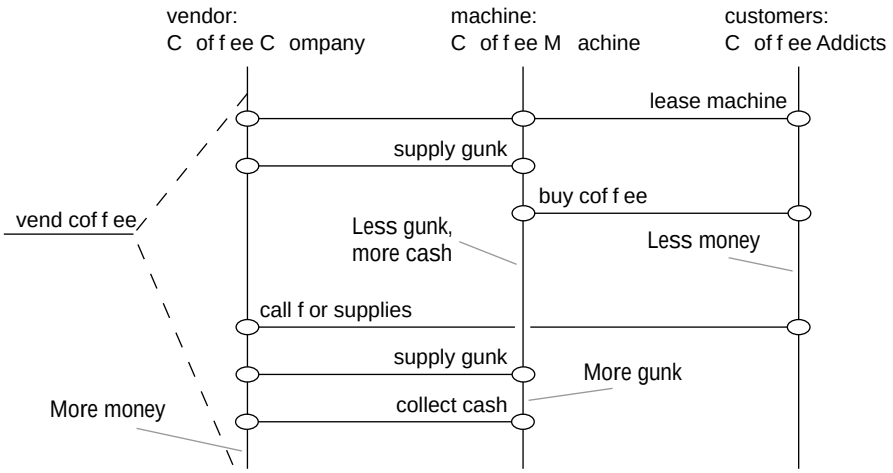


Figure 6.8 Refinement into further joint actions.

1. CLOS is an exception: Its operations are not attached to any particular receiver. As with Java and C++, there may be several operations with the same name and different parameter lists; but the operation to be executed is chosen at runtime on the basis of the classes of all the parameters (not just the receiver, like the other languages). Catalysis works as well for CLOS as it does for Java and so on because multireceiver messages are a type of action.

6.1.5.1 Refining Actions

We can zoom into, or refine, the action to see more detail. What was one action is now seen to be composed of several actions (see Figure 6.8). Each of these actions can be split again into smaller ones, into as much detail as you like. Some of the actions might be performed by software; others might be performed by some mixture of software, hardware, and people; still others might be the interactions between those things. At any level—deep inside the software or at the overall business level—we can treat them the same way. Catalysis is a "fractal" method: It works in the same way at any scale.

Notice that the abstract action has not gone away; we have only filled in more detail. It is still the name we give to the accomplishment of a particular effect by a combination of smaller actions, and that effect is still there.

These illustrations might suggest that an action is always made up of a sequence, but often the composition is of several concurrent processes that interact in some way. Recall that *action* is the Catalysis blanket word for process, activity, task, function, subroutine, message, operation, and so on.

We can summarize any kind of action abstraction on a type diagram, showing which collaboration (set of actions) can be abstracted into a single abstract action (see Figure 6.9). The diamond aggregation ("part of") symbol is used to indicate that the abstract action is an encompassing term for compositions of the smaller actions. It shows constituent parts of the abstraction, although we must state separately how they are combined—whether in parallel or sequence—and whether some are optional or repeated. Also, another diagram may show a different set of detailed actions abstracted to the same abstract action.

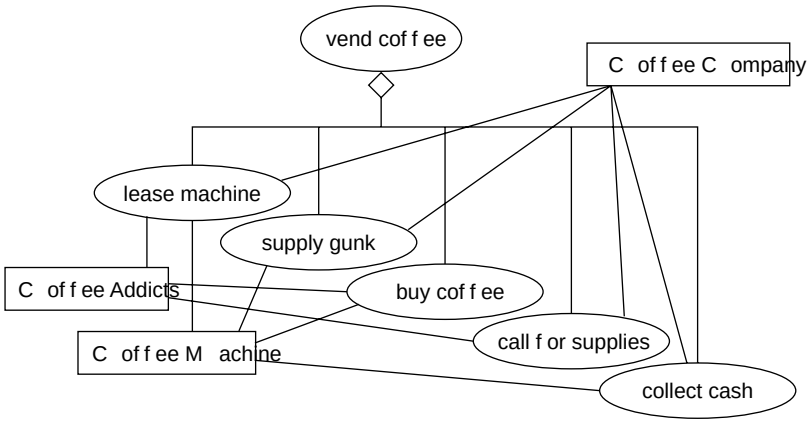


Figure 6.9 Abstract actions shown using aggregation.

6.1.5.2 Summary: Action Abstraction

Action abstraction is the technique of treating a dialog between several participants as a single interaction with a result definable by an effect.

Action abstraction and operation abstraction are both about treating several smaller actions as one. The differences can be summarized as follows.

- In operation abstraction, the initial invocation results in a sequence of smaller actions determined by the design; the abstraction still has the same initial invocation and captures the net desired effect.
- In action abstraction, no invoker need be identified: Any participant can initiate it. The exact sequence is determined by the designs of all participants (some of whom could be human); we can say only what the smaller actions are and the constraints on how they might be combined. Also, the abstract action may never be directly "invoked" at the detailed level.

Action abstraction comes from the idea of transaction, developed in the database world in the 1970s, although it is a natural usage in everyday conversation.

6.1.6 Object Abstraction

We can refine, or zoom into, objects, splitting any of the vertical bars on the diagram into several. Thinking about it in more detail, we realize that the vendor company has different departments that deal with different parts of the business. Also, the customer organization will have users as well as a site manager who establishes a liaison with the vendor (see Figure 6.10).

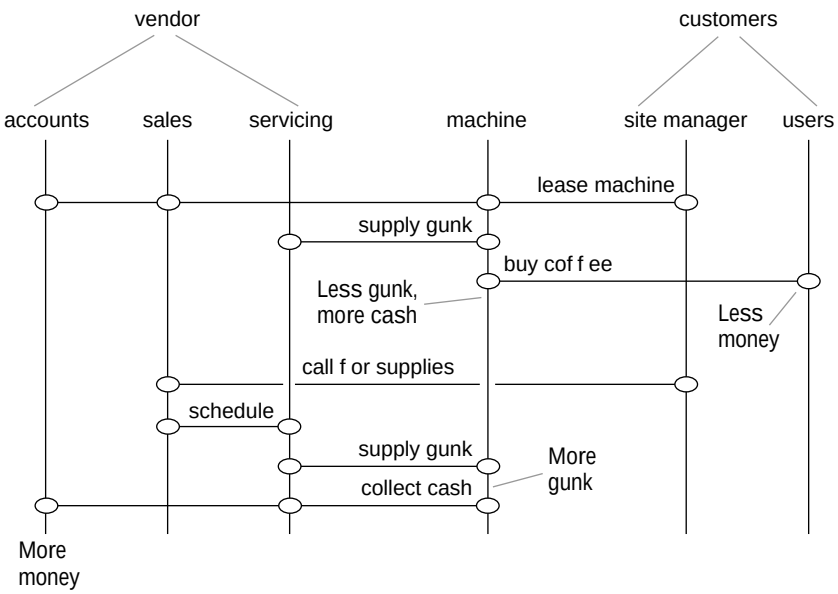


Figure 6.10 Abstracting objects.

Again, the more-abstract objects have not gone away. The company is still there; it is what we call a particular configuration of interrelated smaller objects. Again, each object can be split further into smaller parts: servicing may turn out to be a department full of people having various smaller roles.

Just as what characterizes an action is its effect, so what characterizes an object is the set of actions it takes part in—its type. There may be many refinements that will satisfy one abstract object type. (Indeed, there may be refinements that successfully satisfy several roles: Some small companies have only a single object that plays the roles of accounts, sales, and servicing.)

Some of the objects may be software components. For example, zooming in on the Accounts department would probably reveal some combination of people and computers, and more detail on the computers would reveal a configuration of software packages, and going into them would reveal lines of Cobol or, if we're lucky, objects in an OO language. The same thing would happen if we peered into the coffee vending machine. And we can continue using the same interaction sequence diagrams (and other tools) right down into the software.

The relationship between an abstract object and its constituents can be shown on a type diagram (see Figure 6.11). The diamond again indicates the refinement relationship. Again, it doesn't by itself give us every detail about any existing constraints between the constituents of one abstraction.

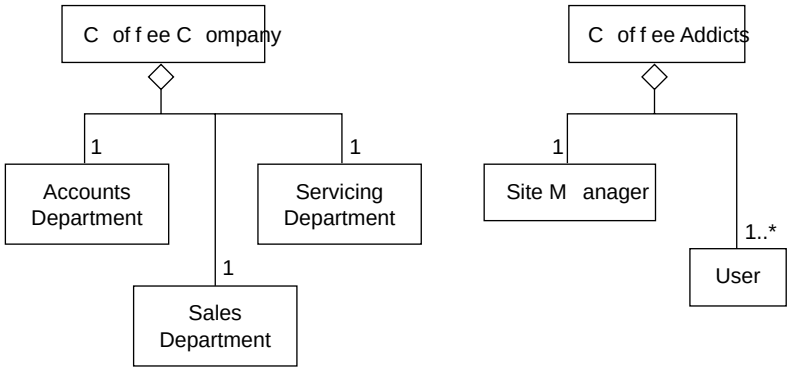


Figure 6.11 Abstract object shown using aggregation.

6.1.6.1 Summary: Object Abstraction

Object abstraction means to treat a group of objects—whether in software, in a human organization, or in a mechanical assembly—as one thing.

The idea is as old as language and was discussed by Plato, Michael Jackson, and others—often beginning with "How many parts of a car must you change before it's a different car?" or "Are you the same person you were when you were born?" The examples

serve to highlight the idea that the identity of anything is, in the end, a model constructed for our convenience rather than something inherent.

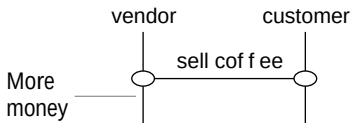
6.1.6.2 Abstracting Objects and Actions Together

It is usual to zoom in or out in both dimensions at the same time. As soon as you resolve each object into several, you must introduce interactions specifically with or between them. Conversely, when you put more detail into an action, you need more objects to represent the intermediate states between the actions.

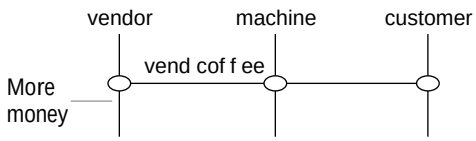
When we looked inside the vendor company, we assigned sales to receive supply requests from the customers, who then schedule a visit by servicing.

By contrast, we left the collection of cash as one action involving both servicing and accounts. This means that we've deferred until later a decision about how that action splits into smaller steps.

Zooming in to an action often involves more objects. As an example, let's go the other way and abstract the original vend coffee action. If the overall requirement is only to get money out of people by giving them coffee, there are more ways of doing it than by installing a machine near them: You could run a café or street stall. So we could have started with this:



and then refined that to this:



Note that the machine is required only when we go to the more detailed scenario of exactly how we're going to sell the coffee.

6.1.7 Zooming In to the Software

In Catalysis, the standard pattern for developing a software system or component is to begin with the business context and represent the business goals in terms of actions and invariants. Then we decide how to meet these goals in a more refined view, with the various roles and interactions within the business.

Some of these interacting objects may be computer systems. We can treat them as single objects and describe their interactions with the world around them. Subsequently, we refine the system into a community of interacting software objects (see Figure 6.12). (A standard OO design is based on a model of the external world so that we now have two of everything: a real coffee cup, a user, and a coin, plus their representations inside the software.) When we look inside the software, we can continue to use the more general multi-

ple-participant actions along with objects that actually represent whole subsystems; but ultimately we get down to the level of individual message sends between pairs of objects.[2]

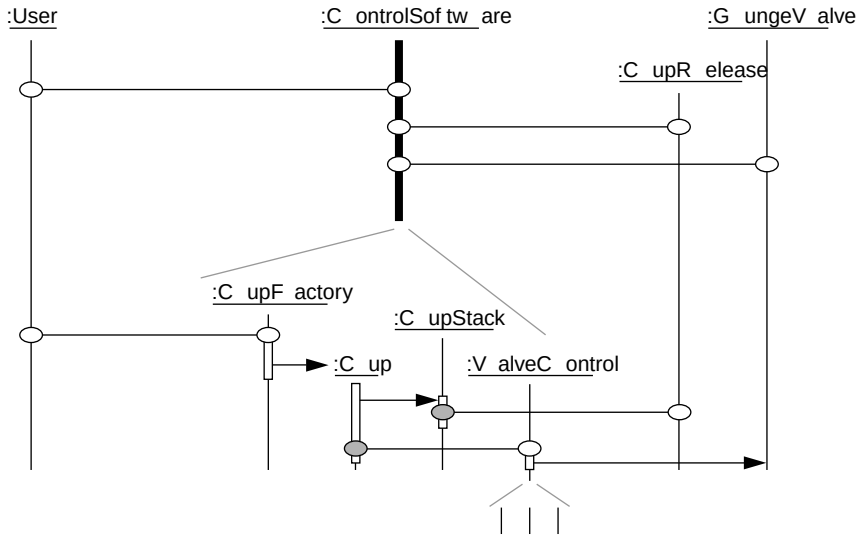


Figure 6.12 A continuum of refinement: real world to code.

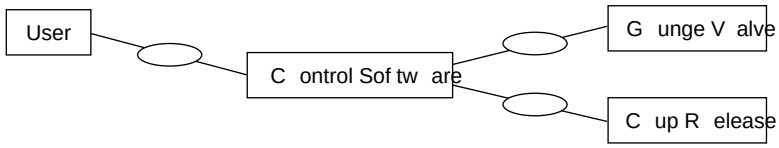


Figure 6.13 Context diagram (collaboration) for one software component.

Again, the sequence diagrams help us illustrate particular cases, but we prefer to document the refinement using type diagrams. This gives us software component context diagrams (see Figure 6.13). It also gives us high-level design diagrams (Figure 6.14).

6.1.8 Reified and Virtual Abstractions

When designing objects inside the software, you have a choice about whether to *reify* abstract objects and actions—that is, represent them directly as software objects—or just

2. A significant difference between Catalysis notation and UML version 1.1 (current at the time of writing) is that UML does not have generalized actions in sequence diagrams; nor are the messages in a sequence diagram understood as instances of use cases. However, at the message-passing level, our sequence diagrams are the same as UML.

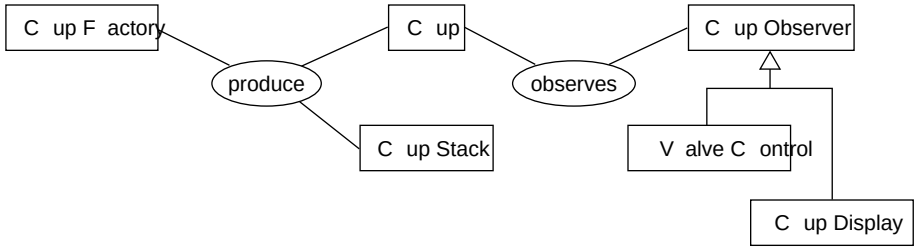


Figure 6.14 Collaboration between software components.

to leave them as ideas in the design that help you understand the various configurations of objects and protocols of messages.

The usual approach is to represent each entire system and each component as an object because it gives something to anchor the parts to. A more difficult decision is whether to make it the *façade* for the group of pieces it represents—that is, the means by which all communication with the outside world should go. Sometimes this works well; it helps ensure that everything inside the component is consistent. In other cases it is not efficient, any more than insisting that every communication with customers go directly through the president of a company.

6.1.9 Composition and Refinement

Other forms of abstraction and refinement, more related to the separation and subsequent joining of multiple, mostly independent views, are covered in Chapter 8, Composing Models and Specifications.

6.1.10 Summary: Kinds of Abstraction

An abstraction presents material of interest to particular users, omitting some detail without being inaccurate. Abstractions make it possible for us to understand complex systems and to deal with the major issues before getting involved in the detail. In Catalysis, we can treat a multiparty interaction as one thing or treat a group of objects as one, and, at different layers of detail, we can choose to change the way we model the business and systems. But through all these transformations, we can still trace the relationships between business goals and program code and therefore understand how changes in one will affect the other.

We've identified four particularly interesting varieties of abstraction.

- *Operational*: Pre/post (or rely/guarantee) specs.
- *Model*: Model attributes may be different from actual implementations.
- *Action*: A complex dialog presented with a single overall pre/post or rely/guarantee spec.
- *Object*: A group of objects presented as one object.

6.2 *Documenting Refinement and Conformance*

When you write a requirements specification (in any style and language you like), you want it to be a true statement about the product that ends up being delivered. If QA shows that the product falls short of the spec, you fix the code; or if it turns out to be impractical to deliver what was first specified, you can change the specification. But one way or another, you can't (or shouldn't!) call the job complete until the delivered design matches the specified requirements.

For valuable components (as opposed to throwaway assemblages of them), we believe in keeping the specification after you've written the code and in keeping it up-to-date. In the long run, the spec (and high-level design documents) helps to keep the design coherent, because people who do updates have a clearer idea of what the component is about and how it is supposed to work. Designs without good documents degenerate into fractal warts and patches and soon end up unmodifiable. Remember that more than 70% of the effort on a typical piece of software is done after it is first delivered and consider whether you want your vision of the design to be long-lived.

This is not to argue that you should complete the high-level documentation before embarking on coding. There are plenty of times when it's a tactical necessity to do things the other way around. Prototypes and rapidly approaching deadlines are the usual reasons. The most useful cycle alternates between coding (to obtain feedback from testing and users and to get things done) and specifying (to get overall insights). Never go beyond getting either cycle 80% complete without working on the other. All we need is that, by the appropriate milestone, the specs should correctly describe the code.

6.2.1 Documenting the Refinement Relationship

The relationship between an abstraction and a refinement is the *refinement relationship*. It is an assertion that one description of a configuration of objects and actions is a more abstract view of another (see Figure 6.15).

6.2.1.1 Refinement and Subtype

The refinement symbol is a version of the subtype symbol.[3] It states that the more detailed model achieves everything expected from the more abstract one. But whereas a subtype symbol says to the reader, "The subtype is defined a priori as an extension of the supertype, having all its properties and more," the refinement symbol says, "The refinement, a self-contained model even without the abstraction, is believed to specify everything defined for the abstraction and more."

3. UML 1.1 makes mention of refinement, with a default notation that uses a stereotype on the generic 'dependency' arrow. Refinement is central to Catalysis; in our presentation here, we have chosen to highlight refinement with a distinguished arrow.

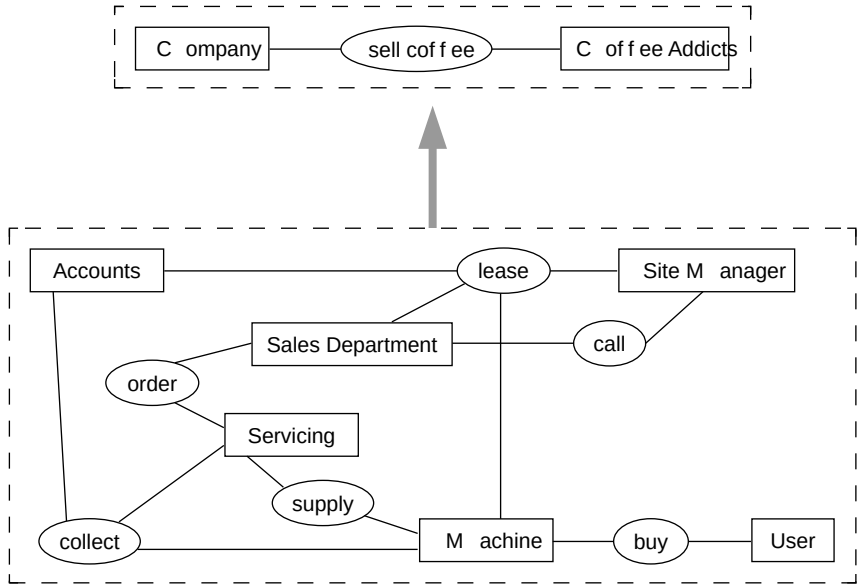


Figure 6.15 The refinement symbol: collaboration refinement.

6.2.1.2 Refinement and Aggregation

There is also a slight difference between the refinement symbol and the diamond aggregation symbol. The diamond makes the abstract and constituent types (or actions) part of the same model. In these models, it is explicit that a w heel is a part of some particular car and that there is some way of knowing which buy action a particular pay is part of; some por-

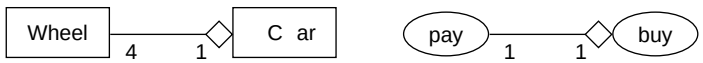


Figure 6.16 Refinement using aggregation.

tion of the retrieval is implied by the aggregation itself, but the full justification is with the refinement.

The aggregation symbol is commonly used when, in a design, you have a reified and distinguished head object representing the abstraction itself (see Figure 6.16). But the refinement symbol is somewhat more general. It says that, even if we didn't think of it that way when creating one model, the other model is nevertheless a more abstract or refined view of it; and we can deal with either model separately.

In some idealized sense, every design project can be thought of as generating a series of refinements even if some of them arise as a result of refactoring or bottom-up abstraction. You begin with a general idea of what is required, refine it to a solid requirements spec,

refine it further to a high-level design, and so on to detailed design and code. For example, you might start with very abstract actions between users and system and refine down to the actual sequences of GUI actions required for each action. If the project is critical enough to be fully documented, each of these refinement layers is written up separately; just as important, the refinement relationships themselves are documented and checked.

Documenting a refinement means writing down the following.

- The reasons for choosing this realization from the alternatives (so that those who follow won't fall down the same pits you fell into along the way).
- A justification for believing you've done the refinement correctly—that is, that the abstraction really describes the realization accurately. (Doing this is an invaluable sanity check and helps reviewers and maintainers.)

Because refinement is a many-many relation, the refinement documentation shouldn't properly attach to either the abstraction or the refinement but rather to the refinement relationship between them. (A component you found in a library may be a good realization of your requirements, but presumably it will fit the requirements of others as well.)

If you're designing a nuclear power station or a jumbo jet, we hope you would take all the preceding writing and verification very seriously, with each layer individually written up and each refinement carefully established. But for most of us, it's both acceptable and desirable to opt for the somewhat more practical solution of clarifying some essential issues at the requirements level, then working on the design and code while resolving other issues, and only then updating a few class diagrams.

Well, maybe. In the new world of component-based development, the successful components will be those that interoperate with many others. Each interface will be designed to couple with a range of other components and must be specified in a way that admits any component with the right behavior and excludes others. A designer aiming to meet a spec should be confident that the component works and should be able to justify that belief.

We should therefore have some idea of what it means to conform to a specification: what must be checked and how you would go about it—in other words, documenting the refinement relationship.

6.2.2 Traceability and Verification

It is important to be able to understand how each business goal relates to each system requirement and how each requirement relates to each facet of the design and ultimately each line of the code. Documenting the refinement relationships between these layers makes it easy to trace the impact of changes in the goals.

Traceability is a much-advertised claim of object-oriented design: Because the classes in your program are the same as in your business analysis, so the story goes, you should easily be able to see the effects on your design of any changes in the business. But anyone who has done serious OO design knows that in practice, the designs can get pretty far from this simple ideal. Applying a variety of design patterns to generalize, improve decoupling,

and optimize performance, you separate the simple analysis concepts into a plethora of delegations, policies, factories, and plug-in pieces.

© ***traceability*** The ability to relate elements in a detailed description to the elements in an abstraction that motivate their presence and vice versa; the ability to relate implementation elements to requirements.

Documenting the refinement relationship puts back the traceability, showing how each piece of the analysis relates to the design.

In safety-critical systems, it is possible to document refinements precisely enough to perform automatic consistency checks on them. However, achieving this level of precision is rarely cost-effective, and we do not deal with that topic in this book.

For the majority of projects, it is sufficient to use pre- and postconditions as the basis of test harnesses and to document just enough of a refinement that other developers and maintainers clearly see the design intent. We'll see how to do that later in this chapter.

6.3 *Spreadsheet: A Refinement Example*

The sections that follow look in more detail at the four main kinds of refinement we mentioned earlier. This section introduces an example that runs through those sections.

6.3.1 A Specification for a Spreadsheet

Let's look first at what can be done with a good abstract model. It's a model of a self-contained program, but it could equally well be a component in a larger system.

Figure 6.17 shows a model of a spreadsheet together with a dictionary interpreting the meaning of the pieces in the model. A spreadsheet is a matrix of named cells, into each of which the user can type either a number or a formula. In this simplified example, a formula can be only the sum of two other chosen cells (themselves either sum or number cells).

The model shows exactly what is expected of a spreadsheet: that it maintain the arithmetic relationships between the cells no matter how they are altered. In particular, the invariant Sum::... says that the value of every Sum cell is always the addition of its two operands.

Notice that this is very much a diagram not of the code but rather of what the user may expect. The boxes and lines illustrate the vocabulary of terms used to define the requirement.

The box marked Cell, for example, represents the idea that a spreadsheet has a number of addressable units that can be displayed. It doesn't say how they get displayed, and it doesn't say that if you look inside the program code you'll *necessarily* find a class called Cell. If the designer is interested in performance, some other internal structure might be thought more efficient. On the other hand, if the designer is interested in maintainability, using a structure that follows this model would be helpful to whoever will do the updates.

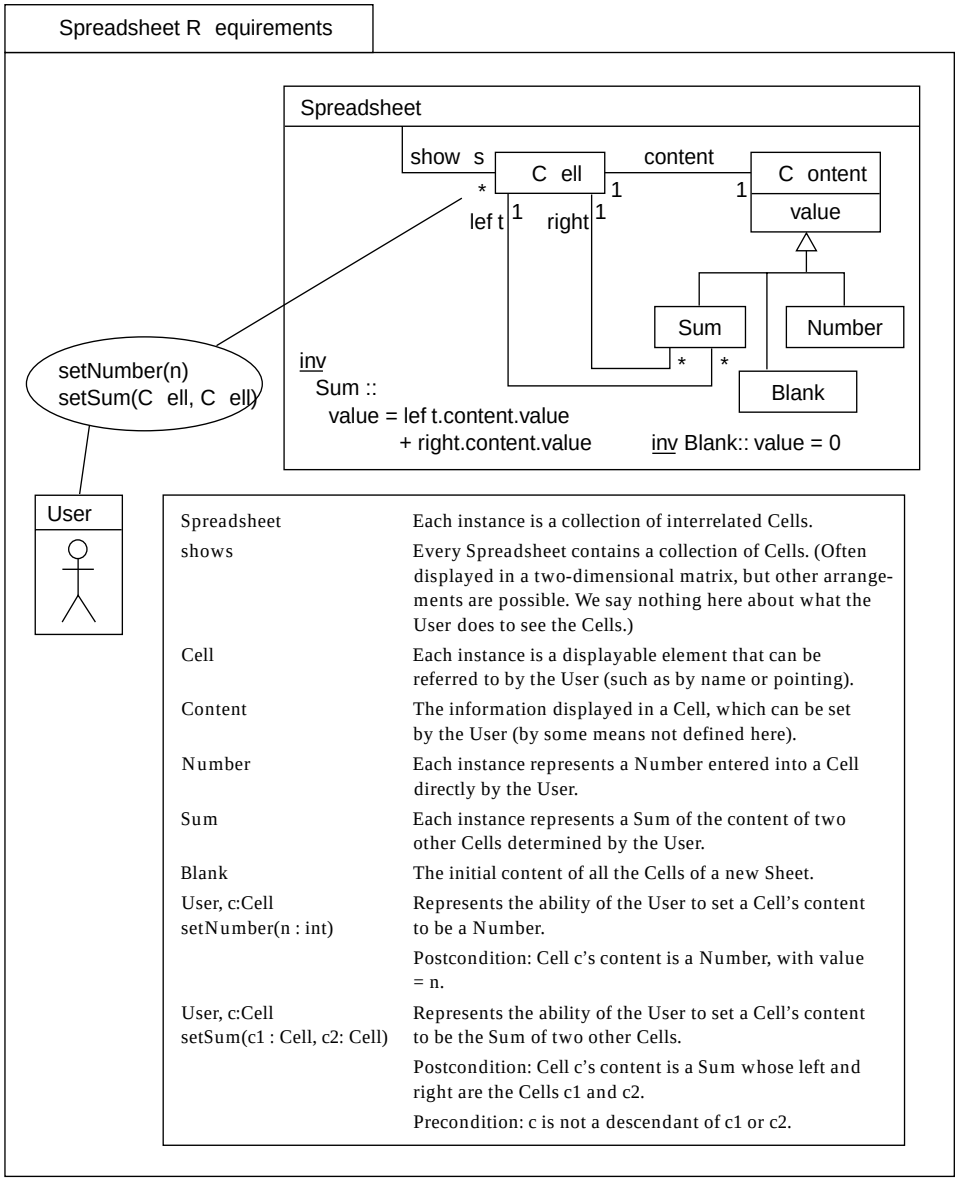


Figure 6.17 Model for a spreadsheet.

The model doesn't even say everything that you could think of to say about the requirements. For example, are the Cells arranged in any given order on the screen? How does the user refer to a Cell when making a Sum? If not all the Cells will fit on the screen at a time, is there a scrolling mechanism?

It's part of the utility of abstract modeling that you can say or not say as many of these things as you like. And you can be as precise or ambiguous as you like; we could have put the {Sum::... invariant as a sentence in English. This facility for abstraction allows us to use modeling notation to focus on the matters of most interest.

6.3.1.1 Using Snapshots to Animate the Spec

Although (or perhaps because) the model omits a lot of the details you'd see in the code, you can do useful things with it. For example, we can draw snapshots: instance diagrams that illustrate clearly the effect each operation has.

Snapshots illustrate specific example situations. Figure 6.18 shows snapshots depicting the state of our spreadsheet before and after an operation. (The thicker lines and bold type represent the state after the operation.) Notice that because we are dealing with a requirements model here, we show no messages (function calls) between the objects; they will be decided in the design process. Here we're concerned only with the effects of the operation invoked by the user. This is part of how the layering of decisions works in Catalysis: We start with the effects of operations and then work out how they are implemented in terms of collaborations between objects.

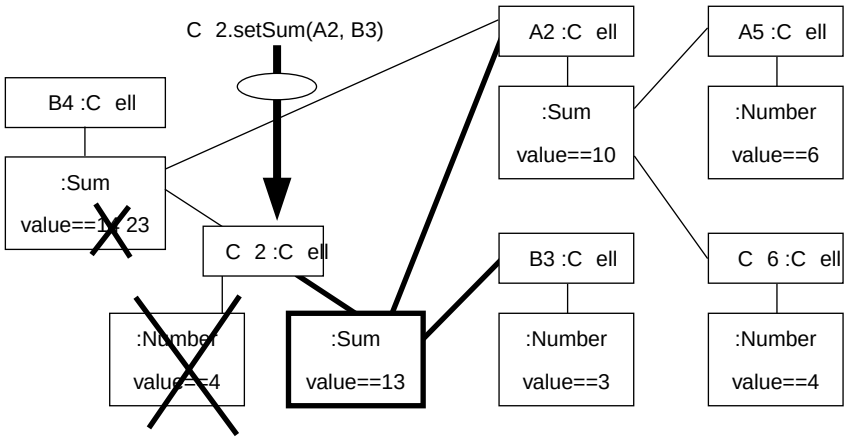


Figure 6.18 Spreadsheet snapshots.

6.3.2 An Implementation

Now let's consider an implementation. The first thing to be said is that the program code is much larger than the model, so we'll see only glimpses of it. Here is some implementation code for a spreadsheet:

```
package SpreadSheetImpl_1;

class SpreadSheet_I                    // This class implements SpreadSheet
{
    private C  ell_I[ ] cells;                    // array of cells of my spreadsheet
```

```
        ...          // various code here
}

class C ell_I
{
        private int m_value;                        // The current value of the C ell
          private Sum_I sumpart;                    // Null if it's a plain number
          public int value ( ) { return m_value; }
          // w ill need some mechanism to keep m_value in sync w its sumpart!
          ... // M ore code f ormanipulating C ells goes here
}

class Sum _I                                        // R epresents Sums
{
        private C ell_I[ ] operands;                // An array of several operands
        int get_value ( )
        {       int sum=0;
                f or(int i= 0; i<operands.length; i++)
                    sum += operands[i].value( );
        }
... // M ore code ...
}
```

The (|_|) suffixes distinguish the implementation. The first thing a reviewer might notice is that the classes I have written don't seem to correspond directly to the classes mentioned in the specification. Their attributes are different, and so on. "We are doing object-oriented design," says the reviewer. "Your code should mirror the spec. It says so in 50 different textbooks."

I am quick to my defense. Point (a): encapsulation. The spreadsheet as a whole, seen through the eyes of users (including other programs driving it through an API), does exactly what the spec leads them to expect. They won't know the difference. This is encapsulation, something that is "also mentioned in about 150 different books," I point out.

Point (b): engineering. Whereas the spec was written to be easily understood and general to all implementations, my particular implementation is better. It works faster, uses fewer resources, and is better decoupled than some amateur attempt that slavishly follows the model in the spec. And for many programs, there would be practical issues such as persistence not dealt with in the spec.

"And finally," I add, "my program is a whole lot more than just a spreadsheet. To use it as such is to play 'Chopsticks' upon the mighty organ of a grand cathedral; to ask Sean Connery to advertise socks." In other words, the spec from my point of view is partial, expressing the requirements of only one class of user; so the implementation classes you see here are chosen to suit a much broader scheme. Nevertheless, it is able to function merely as a spreadsheet when required, and I wish it to be validated as such against the spec.[4]

6.3.3 The Refinement Relationship

Whether you believe all that about my spreadsheet is not important here. Certainly, there are many times when performance, decoupling, or a partial spec leads to differences between model and code. So the reviewer is faced with trying to determine whether there is some correspondence between them: whether the code conforms to the spec (or refines it).

Naturally, proper testing will be the final judge. But understanding the conformance relationship allows an earlier check, which can clarify the design and the rationale for the differences. What's more, it provides traceability: the ability to see how any changes in either the spec or the code affect the other.

As we've seen, we can distinguish a few main primitive kinds of refinement. Combinations of them cover most of the valid cases: you can explain most design decisions in terms of them. In a large development, the usual layers of requirements, high-level design, detailed design, and code can be seen as successive refinements.

Understanding refinement has several advantages.

- It makes clear the difference between a model of requirements and a diagram that more directly represents the code (one box per class).
- It makes it possible to justify design decisions more clearly.
- It provides a clear trace from design to implementation.

Many of the well-known design patterns are refinements applied in particular ways. The refinements we're about to discuss are, in some sense, the most primitive design patterns; they are themselves combined in various ways to define the more popular design patterns.

We'll now see examples of the four refinements we looked at in Figure 6.1.

6.4 *Spreadsheet: Model Refinement*

The reviewer begins by getting me to produce a drawing of my code. Figure 6.19 shows a view focusing on the external user operations and their postconditions. You can see the direct correspondence between the static model and the variables. Indeed, there are tools that will take the code and produce the basis of the diagram.

```
class C ell_I
{ private int value;
  Sum_I sumpart;   // null f ora Number
...
class Sum_I
{ C ell_operands [ ];      // array
...
```

4. Presumably, the spec has not said anything about my program's 94MB size and the download time to Web users other than Sean Connery.

The reviewer begins with how the information in the model is represented.

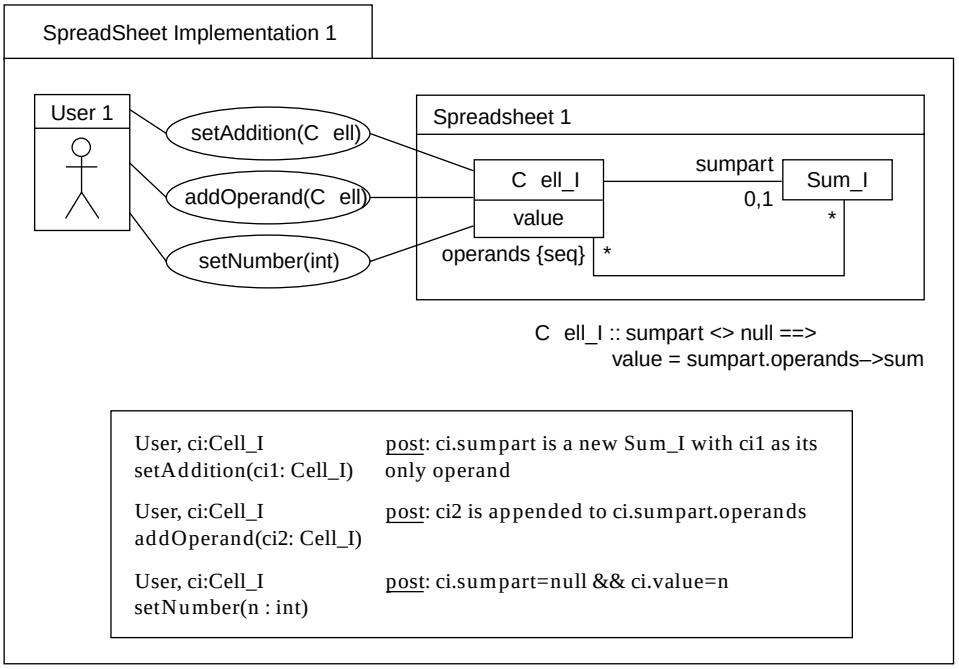


Figure 6.19 A picture of my code.

"How is the spec's Sum represented?" she asks.

"By my Sum_I," I reply.

"So where are the lef tand right attributes of a Sum?"

"No problem," I answer. "All the information mentioned by the requirements is there—it's just that some of the names have changed. If you want to get the lef tand right operands of any Sum, look at the first and second items of my operands array. But because the requirements don't call for any operations that directly ask for the left or right, I haven't bothered to write them." Nevertheless, anyone using my code would see it behaving as expected from the spec.

6.4.1 What a Type Model Means and Doesn't Mean

The types in a model provide a vocabulary for describing a component's state. The terms can be used to define the effects of actions. However, the model does not provide any information about the internal structure of the component.

A static model (types, attributes, and associations) provides, by itself, no useful information about what behavior to expect. Only the action specifications based on it provide

that. The complete specification is a true one if the statements it makes or implies about the component's behavior (response to actions) are always correct. Features of a static type model not used by action specifications are redundant, having no effect on the specification's meaning.

6.4.2 Documenting Model Conformance with a Retrieval

The general rule is that, for each attribute or association in the abstract models, it should be possible to write a *read-only* function in the implementation code that abstracts (or retrieves) its value. Here are the retrievals for Sum_I I've just mentioned to my reviewer:

```
class Sum_I
{    private Cell_I[ ] operands;    // array
     Cell_I left( ) {return operands [0]; }
     Cell_I right ( ) {return operands [1];}
     ...
```

These abstractions happen to be particularly easy; the correspondence to the spec model is not very far removed. Others are more complex. But it doesn't matter if an abstraction function is hopelessly inefficient: It need only demonstrate that the information is in there somewhere. Nor does it matter if there is more information in the code than in the model. I can store more than two operands, although readers of the official spec won't use more than two.

6.4.3 Drawing a Model Conformance

Retrievals can be made more clear with a diagram. It can be helpful to draw both models (or at least parts of them) on a single diagram. You can then visually relate the elements across the refinement using associations and write invariants that define the abstraction functions for all attributes in the spec.[5] These associations, introduced specifically for this purpose, are distinguished with a <<retrieval>> tag or stereotype. (We often abbreviate that to a // marker, although in Figure 6.20 we've shown both.) Figure 6.20 shows that each Cell_I in the implementation corresponds one-to-one with a Cell in the spec; the same is true for Sum_I and Sum. All we need is to document how the attributes of Cell or Sum can be computed from the attributes of Cell_I or Sum_I. For example:

```
Sum ::        left=     impl1.operands[1].abs
      and     right =   impl1.operands[2].abs
      and     value =   impl1.container.value
```

Notice what's happening: we start with a part of the spec and go through its attributes, showing how they are realized in this implementation, which is called impl1 (not just impl—it might have many implementations we've not seen yet). The left is given by our

5. The specification model will generally be in one package and the implementation in another. (Packages are dealt with in Chapter 7.) There may be more than one implementation, so we don't want to put them all in one package. The conformance retrieval information may be with the implementation or in its own package.

implementation's first operand—well, not quite, because that's a C ell_I. Actually, it's the abstract C ell represented by its first operand—hence, the abs at the end.

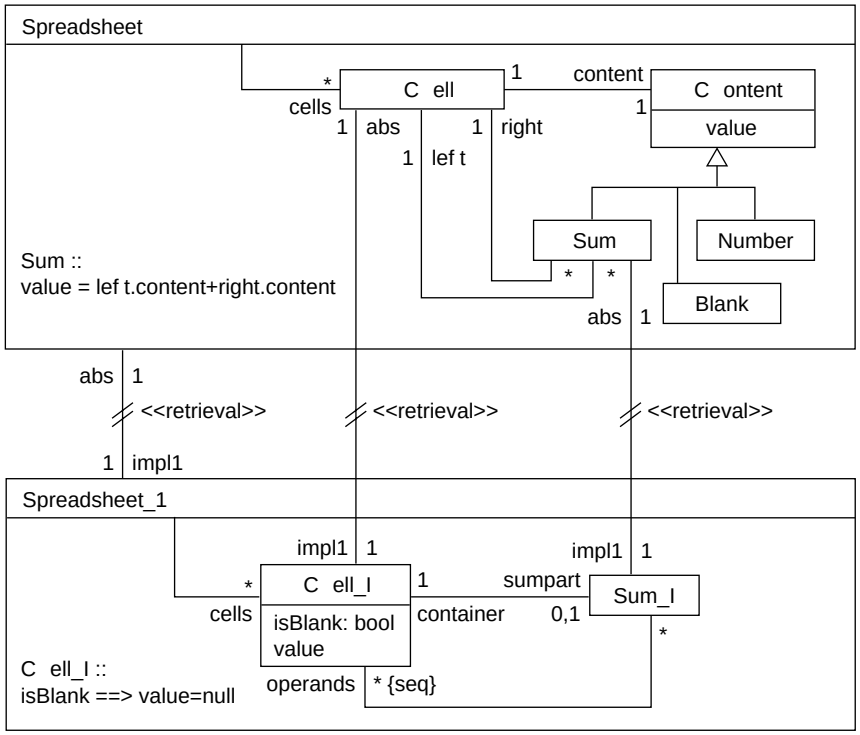


Figure 6.20 Retrieval diagram.

We can say the same kind of thing about C ell:

```
C ell::          content.value = impl1.value
          -- my content's value is represented by my implementation's value
and              if (impl1.isBlank) abs.content : Blank
                      -- impl1's isBlank flag means I am a Cell with a Blank content
                 else if (impl1.sumpart = null) abs.content : Number
                      -- if my implementation has no sumpart, my content is a Number
                 else (content : Sum) and content = impl1.sumpart.abs
                      -- otherwise my content is a Sum, as represented by my
                         implementation's
                      -- sumpart --- see its retrieval for details
```

And finally we can say the same thing about the whole spreadsheet:

```
SpreadSheet_1 :: abs.cells = cells.abs
     -- I represent the Spreadsheet whose Cells are all the abstractions that my
        Cell_Is represent
```

Writing the retrieval functions doesn't directly depend on drawing the retrieval relations, but it helps where the correspondence is more or less one-to-one. Notice that we don't, for example, have a direct correspondence to Number.

6.4.4 Testing Using Abstraction Functions

QA departments may insist that such retrieval (abstraction) functions should be written down or even written into the code. Even though these functions are not always used in the delivered code, they are useful.

- Writing them is a good cross-check, helping to expose inconsistencies that might otherwise have been glossed over.
- They make an unambiguous statement about exactly how the abstract model has been represented in your code.
- For testing purposes, testbeds can be written that execute the postconditions and invariants defined in the requirements models. These talk in terms of the abstract model's attributes, so the abstraction functions will be needed to get their values.

  For example, recall that we wrote one of the invariants as

  ```
  Sum:: value = left.content.value + right.content.value
  ```

Becuase we have defined what value, left, and right mean in terms of this implementation, we can rewrite it, substituting the definitions of each of them:

```
Sum :: impl1.container.value  =  impl1.operands[1].abs.content.value
                              +  impl1.operands[2].abs.content.value
```

The impl1 at the start of each of these expressions says that we are talking about the implementations. So maybe it would be simpler to write the invariant so that it applies to all Sum_Is instead:

```
Sum_I :: container.value      =  operands[1].abs.content.value
                              +  operands[2].abs.content.value
```

This is an invariant we could execute in the implementation in debug mode. We could make one further simplification to make more clear what is happening. Evaluating the expressions operands[n].abs will give a Cell, and the retrievals say that Cell::content.value = impl1.value. So we could rewrite the invariant:

```
Sum_I :: container.value      =  operands[1].abs.impl1.value
                              +  operands[2].abs.impl1.value
```

But that's still a bit long-winded. Something such as abs.impl1 is running one way up a one-to-one association only to come back down it again—the two cancel out. So we get

```
Sum_I :: container.value      =  operands[1].value + operands[2].value
```

6.4.5 Model Conformance: Summary

We've seen how a model can be very different from the code and still represent the same information. Now, as we've said before, the Golden Rule of object-oriented design is to

choose your classes to mirror your specification model. When that is possible, the abstractions are trivial, a one-to-one correspondence. But there are several circumstances when it isn't possible, and model refinement gives us a way of understanding the relationships. Typical cases include the following.

- The model that gives best execution performance is very different from one that explains clearly to clients what the object does.
- The implementation adds a lot to the specified functionality. It is possible for one object to satisfy several specifications, especially when it plays roles in separate collaborations (as we will see in later chapters). Each role specification will have its own model, which must be related to the implementation.
- You specified a requirement and then bought a component that comes with its own spec. The first thing you must work out is how its model corresponds to yours.

We've also said before that it is a matter of local policy how formal your documentation must be. When you're plugging components together to get an early product delivery, you don't care about all this. But when you're designing a component you hope will be reused many times, it is worth the extra effort. And even if you don't go to the trouble of writing the abstraction functions, it is useful to do a mental check that you believe they could be written if you were challenged to.

6.4.6 Testing by Representing the Specification in Code

What the Quality Assurance department really wants is to be able to represent a spec in code so that it can be run as a test harness. They want to be able to write one set of invariants, postconditions, and so on that every candidate implementation can be tested against. As far as they are concerned, the spec writer writes a spec and associated test assertions. Each hopeful designer must supply two things: the design plus a set of abstractions that enable the test assertions to execute.

This rigorous view of specification and testing leads to a view in which all models can be cast into program code (something that is not so tedious as it was before code-generating tools). The types in a specification turn into abstract classes, of which the designer is expected to supply implementations. Figure 6.21 on the next page shows this done for the invariants; postconditions are omitted.

(In Java, you'd think spec types would be written as interfaces. Unfortunately, if we want to put the invariants and postconditions into the types themselves in real executable form, they must be classes. This has the uncomfortable effect of disallowing one implementation class from playing more than one role. An alternative is to put all the test apparatus in a separate set of classes that interrogates the states of the types. Again, we find ourselves applauding Eiffel, in which all this is natural and easy.)

If we can write the whole thing, spec and all, in code, we can also show both the abstract model and the more detailed design in one picture—see Figure 6.22 on page 245. The Cell and Sum refinements are only model refinements, because the abstraction did not promise any behavior requirements on those types.

Specification as Code

```
package SpreadSheetSpec;

abstract class SpreadSheet
{
   public abstract C  ell [ ] show  s ();
         // C  ell [ ]         - - array of  C  ells
         // abstract       - - header only, no body

// invariant true if  all constituents OK
   public boolean invariant ( )
       { boolean inv= true;
           f or (int i= 0;
                 i<show  s () .length; i++)
              inv &  &  = show  s () [i] .invariant ();
           return inv;
}        }

abstract class C  ell
{   abstract C  ontent content ();
//invariant true if  content is OK
   boolean invariant ( )
       {  return content( ) .invariant(); }
}
abstract class C  ontent
{   abstract       int value ( );
//  def ault invariant -  depends on subclass:
    boolean invariant ( ) { return true; }
}

abstract class Sum extends C  ontent
{
     abstract    C  ell lef t();
     abstract    C  ell right();
//  crucial spreadsheet invariant
    boolean invariant ( )
   {  return super.invariant() &  &
         value() ==
               lef t() .content() .value( )
         +       right() .content() .value( );
}  }

abstract class Number extends C  ontent
{
    abstract       void set_value (int v);
       // post:     v == value()
}

class Blank extends C  ontent
{
    boolean invariant ( )
    {    return super.invariant()
                    &  &   value() ==0 ;
    }
    // This is so obvious . . . let' s just do it
    public int value ( ) { return 0; }
}
```

Implementation (part)

```
package SpreadSheetImpl;
import SpreadSheetSpec;

class SpreadSheet1 extends SpreadSheet
       // This class implements SpreadSheet
{  private C  ell_I [ ] cells;
//retrieval:
     public C  ell [ ] show  s ( )
     {    C  ell [ ] r= new   C  ell [cells.length];
          f or (int i= 0; i<r.length; i++)
            r[i]= cells[i];
          return r;
}    }

class C  ell_I extends C  ell
{    private boolean isBlank= true;
     private int m_value;          // current value
     private Sum_I sumpart;    // null f or Number
//   retrieval as a C  ell:
     public C  ontent content ()
     {    if  (isBlank) return new   Blank( );
          else if  (sumpart==null)
               return new   NumberC  ellAdapter(this);
          else
               return sumpart;
     }
     public int value () {if  (sumreturn m_value)}
//   services retrieval of  Number:
     void set_value (int v) { m_value= v; }
}

class Sum_I extends Sum
{    private C  ell_I [ ] operands;
     public int value ( ) { . . .add operands. . . }
//   retrievals as a Sum:
     public C  ell lef t ( )
     {    if  (operands.length == 0)
            return new   C  ell_I ( ); //blank
          else return operands[0];
     }
     public C  ell right ( )
     {    if    (operands.length <= 1)
              return new   C  ell_I ( ); //blank
          else return operands[1];
}  . . .  }

//  This class is used f or retrieval
//  w  hen debugging - -  not required in delivery
    class NumberAdapter extends Number
{    private C  ell_I myC  ell;
     NumberAdapter (C  ell_I c)  // constructor
          {    myC  ell= c; }
     public int value ( )
          {    return myC  ell.value(); }
     public void setV  alue (int v)
          {    myC  ell.setV  alue(v); }
}
```

Figure 6.21 Specification directly translated to code (*left*) and implementation with retrievals (*right*).

But our reviewer has been thinking. "I notice your left and right return Cell_I, so that must be your representation of Cell right?" she says. "So what's a Cell_I's content?"

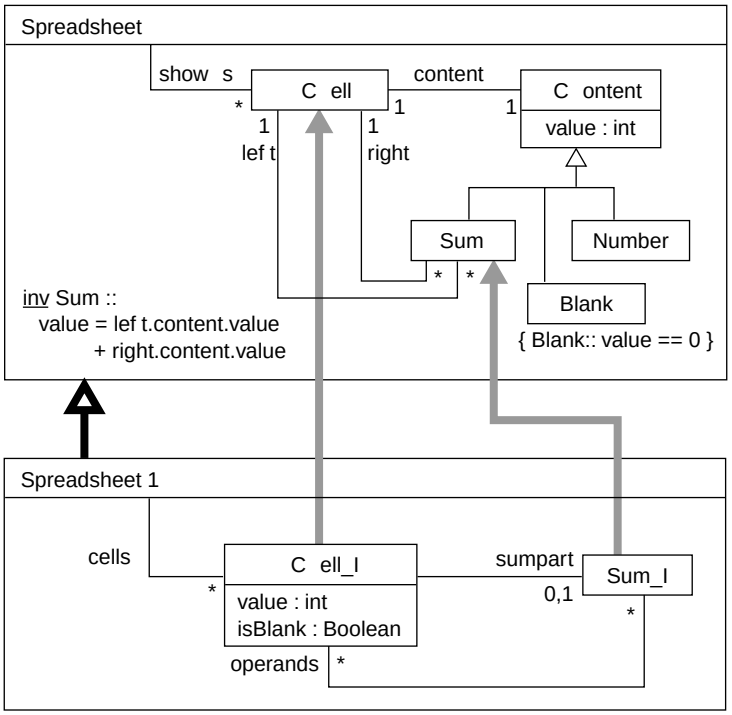


Figure 6.22 Spec and code, showing main correspondences.

"In my terms, that's its sumpart," I reply.

"But that only works if the Cell's content is a Sum," she says. "What if it's a Number or a Blank?"

Well, that's a good question. The spec always models every Cell as having a Content even if it's just a plain Number, whereas I keep the value in the Cell_I itself and use an extra object only to deal with Sums. The information is all in there but is distributed in a different way. But it presents an obstacle to the executable invariants idea: A term such as left().content().value() wouldn't work where left() is a plain number cell, because it doesn't have a content.

What I want to say is that expressions in the spec such as content.value should be translated into the terms of the implementation as a whole: The content.value of a Cell_I is its sumpart.value if it's a sum and is its own variable m_value otherwise. This is perfectly reasonable if all I want to do is document the abstraction function and persuade my reviewer that my code is OK.

But for executable test assertions, content() must return something that will then return the appropriate value(). This leads to the invention of the class NumberAdapter (so now we have abstraction classes as well as functions). It can be kept fairly minimal. All it must do is know our implementation well enough to extract any information required by the test assertions in the spec type Number.

So the general pattern for executable abstractions is that for every type in the spec, the designer provides a direct subclass. Sometimes these can be the classes of the implementation; in practice they often must be written separately, mostly because your classes have more interesting things to be subclasses of. Each adapter retrieves from the implementation that part of the component's state that its specification supertype represents. Notice that our adapters are created only when needed (see Figure 6.23).

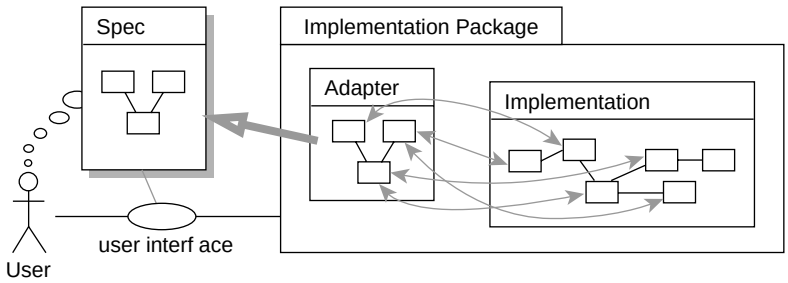


Figure 6.23 Test by adapting the implementation.

What has happened to our ideal of encapsulation? We started with the idea that internal workings unseen by the user could be designed in any way you like; now we've had to put back all the structure of the model.

Well, not quite. The adapter classes need only translate and are there only for verification. The real implementation still does the hard work. And you'll need them only if your QA department is pretty stringent.

As it turns out in practice, adapters of this kind are frequently needed for each external interface of a component, whether it is a user interface or an interface to another component (see Figure 6.24). This is because the component's internal state must be translated into the view understood by each external agent. (For human users, the GUI usually encompasses the adapter.)

6.4.7 Specifications in Code: Summary

Specifications can be written not only as pictorial models but also in the form of executable test frameworks. The benefit is a much stronger assurance of conformance, especially where there may be a variety of candidate implementations.

Implementors must provide executable abstraction functions to translate from the component's internal vocabulary to that of the specification. Often, this leads to providing an

adapter, a set of classes directly mirroring the types in the spec. However, adapters can be useful at the interface of a component in addition to their role in verification.

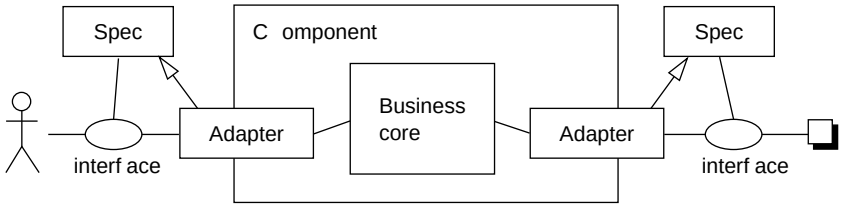


Figure 6.24 Adapters for other interfaces.

6.5 *Spreadsheet: Action Refinement*

The next thing my code reviewer notices is that nowhere is there a function setSum(Cell, Cell)I explain that I have decided to refine this action to a finer-grained series of interactions between the user and the spreadsheet (see Figure 6.19 earlier). To set a cell to be the sum of two others as per requirement, the user performs this scenario:

- Select the cell in question by clicking the mouse.
- setAddition: type = and click one of the operand cells.
- addOperand: type + and click on the other.

The requirement is provided for by a combination of features in my implementation. My "=" operation turns the Cellinto a single-operand sum, and each "+" operation adds another operand. So although there is no single operation with the signature setSum(Cell, Cell)—either at the user interface or anywhere inside the code—the user can nevertheless achieve the specified effect.

It is an important feature of a Catalysis action that, without stating how, it represents a goal attained by a collaboration between the participants. The goal can be unambiguously documented with a postcondition or with a guarantee condition. A *conformant* implementation is one that provides the means of achieving the goal.

Different implementations require different behavior on the part of every participant, because they will involve different protocols of interaction. A user who knows how to use my spreadsheet implementation will not necessarily know how to use another design. It is the collaboration that has been refined here and not the participants individually.

6.5.1 Action Conformance: Realization of Business Goals

In general, the specification actions are about the business goals of the system—for example "The user of our drawing editor must be able to duplicate picture elements and must be able to copy them from one drawing to another." The actions that we provide break these larger

goals into decoupled pieces. We invent a clipboard and provide cut and paste operations with which the user is able to achieve the stated goals.

Here's another example: "The customer of our bank must be able to get money at any time of the day or night." So we invent cash machines and cash cards and provide the actions of inserting the card into the machine, selecting a service, and so on. The user, with the help of a good user interface, uses these actions to achieve the stated goals.

6.5.2 Checking Action Conformance

We need to check that, for every action defined in the specification, there is a combination of implementation actions that the user could follow to achieve the defined goal. Let's take setSum as an example.

The action specs shown here were given in Figure 6.17 and Figure 6.19:

From the spec

User, Cell:: setSum (ci1 : Cell, ci2 : Cell)	Represents the ability of the User to set a Cell's content to be the Sum of two other Cells. Post: Cell's content is a Sum whose left and right are the Cells c1 and c2.

From the implementation

User, Cell_Ci:: setAddition (ci1 : Cell_I)	Post: ci.sumpart is a new Sum_I with ci1 as its only operand.
User, Cell_Ci:: addOperand (ci2 : Cell_I)	Post: c2 is appended to ci.sumpart.operands. Pre: ci.sumpart <> null. This is already a Sum.

A little thought suggests that a setAddition followed by an addOperand should achieve the effect of a setSum. A comparison of snapshots in the two views will help; the arrows show which links are created by each action (see Figure 6.25).

Now we can see that performing the sequence

<ci.setAddition(ci1), ci.addOperand(ci2)>

should achieve an effect corresponding to the spec's c.setSum(c1, c2). To be absolutely sure, we can use the abstraction functions we worked out earlier.

setSum's postcondition talks about the left and right of Cell. In our implementation, we claim that Cell_Is represent Cells, so in our example snapshot, cin represents cn. We also decided that content.left in the spec is represented by sumpart.operands[0]. So does this sequence of steps achieve that "Cell's content is a Sum whose left is Cell1"? Yes, because the first step makes ci.sumpart.operands[0] =ci1. And does it achieve that c.content.right = c2? Yes, because the second step achieves ci.sumpart.operands[1] = ci2.

6.5.3 Documenting Action Conformance

We can document the refinement as in Figure 6.26. The diamond "assembly" symbol says that there is some way in which the specification effect can be achieved by some combination of the implementation actions. But exactly what sort of combination—concurrent, sequential, some sort of loop—must be said separately.

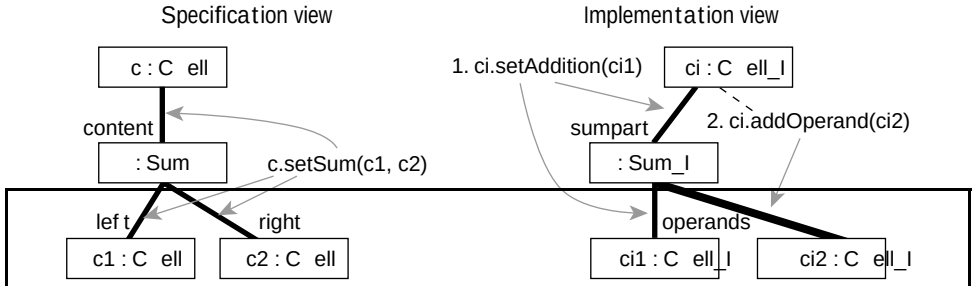


Figure 6.25 Snapshots in specification and implementation.

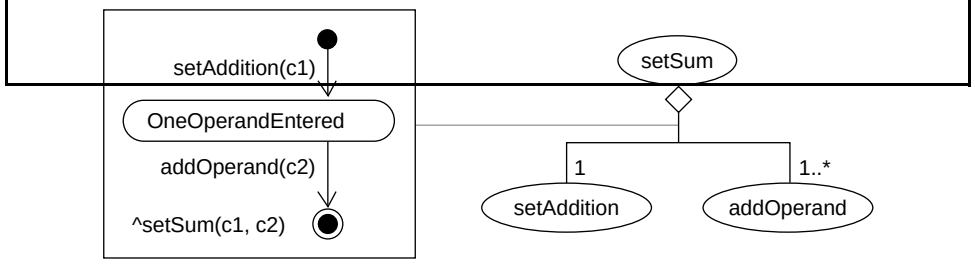


Figure 6.26 Action conformance.

In the case of a sequence, this can be done with a state chart.[6] Each implementation action is a transition on the diagram; each state represents how much of the overall job has been achieved so far. You may need to use additional attributes, with new postconditions on the detailed actions, to make the mapping clear.[7]

This one is simple. The initial setAddition takes us into an intermediate state, OneOperandEntered, from which an addOperand will complete the overall setSum action. This achievement is denoted by the caret mark ^. We do not specify here what happens if addOperand occurs when we're not in OneOpnd or what happens if setAddition is performed again when we're in OneOpnd. Those exceptions can be shown separately.

Names are chosen in the state chart (here, c1 and c2) to indicate how the arguments of the actions are related. You can use the names in guards and postconditions written in the chart to show other constraints and results in more detail.

As usual, diagrams are not intended to be a substitute for good explanation in your natural language. Instead, they are supposed to complement it and remove the ambiguities.

6. We have found that temporal logic handles more general cases in a very concise form. The UML activity diagram is another alternative.

7. For example, Section 4.2.2, Preview: Documenting a Refinement, introduces a counter to count the number of individual item insertions and map to the single abstract action of some quantity of those items.

6.5.4 Testing Action Conformance

Testing action conformance at runtime isn't as easy as just inserting a few lines of code to monitor the postconditions. The problem is that nowhere does my user explicitly say to my implementation, "Now I want to do a setSum." It's the same with our other examples: A user doesn't say to the drawing program, "Now I'm going to move a shape from one drawing to another." Rather, the user just uses the select, cut, and paste operations.

Therefore, we have two options. We can write a test harness that performs the requisite sequences and checks the postconditions by comparing states before and after, or we can perform the equivalent checks manually by following a written test procedure. This is a matter of policy in your project. Each approach will be appropriate in different circumstances. Either way, you are systematically defining test *sequences* based on refinement of abstract actions. And, either way, the documented action conformance should be used to guide the creation of the tests, and the retrievals (whether only documented or actually coded as we saw earlier) provide the mapping between the different levels of the model.

6.5.5 Action Conformance and Layered Design: Action Refinement Brings Model Refinement

Action refinement is nearly always associated with model refinement. To represent the intermediate states, the more detailed model needs more information.

Action refinement is about taking a large interaction with many parameters and breaking it into several steps with fewer and simpler parameters. For example, get_cash(ATM , person, account, $)breaks down to several steps, such as insert_card(ATM çard) and enter_amount($,)each of which identifies only a few parameters at a time. After the first step, the ATM system must remember whose card has been inserted so that when the later $ step happens, it knows which account to debit (see Figure 6.27). The association of "Account x currently using ATM y" is not needed at the more abstract level. Ultimately, the process can be taken down to individual keystrokes and mouse clicks.

In our spreadsheet, we glossed over something of this nature. We originally said that the user first selects a cell and then performs a setAddition operation to identify the first operand. In other words, select(C ell_l)sets some current_f ocusattribute of the spreadsheet as a whole; and setAddition's postcondition should properly have been written in terms of current_f ocus

action setAddition (ci1: C ell_l)

post: current_f ocus.sumpartis a new Sum_I with ci1 as its only operand.

We can take the action refinement even further. How is a setAddition performed? By typing = and clicking in a cell. For that we need an addition to the model to record that after the =, we're now in the "identify C elll or adding" state and to map mouse coordinates to C ell Yes, finally, we've gotten down to something that uses the graphical layout of the spreadsheet.

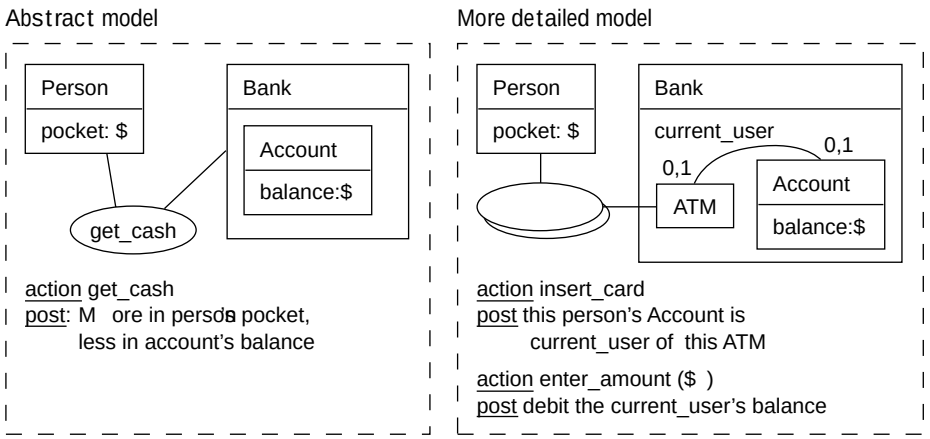


Figure 6.27 Action refinement means intermediate attributes.

6.5.5.1 Reifying Actions

Reification means to make real. We use it to mean making an object from some concept. In a model, we can feel free to represent any concept as an object; in a design, reification is the decision to write a class to represent that concept.

It is often useful to represent an action as an object, particularly an abstract action with refinements. Its purpose is to guide the refined actions through the steps that lead to the achievement of the abstract action's postcondition and to hold the extra information that is always required to represent how far the interaction has progressed.

In the bank example, we might create an ATM_transaction object as soon as a user inserts a card. This object would keep all the information about the account that has been selected, the current screen display, the menu options, and so on.

Reified action objects also form a record of the action after it has completed (for audit trail purposes) and keep the information necessary for an undo operation. This transaction object is also the place to put all the functionality about exceptional outcomes, rollbacks, and so on.

We can see reified actions in real-world business transactions. An order is the business concept representing the progression of a buy action through various subactions such as asking for the goods, payment, and delivery. An account is the reification of the ongoing action of entrusting your money to your bank.

Reified actions are often called *control objects* or *transaction objects*. Whenever we draw an action ellipse on a type diagram, we are really drawing a type of object, which might or might not be reified in an implementation. (See Pattern 14.13, Action Reification.)

It's easy to see the direct correspondence: The participants of the action are drawn as, and are, associations of the reified action; the action's parameters—variable values we don't bother to depict as links on the diagram—are the object's attributes (see Figure

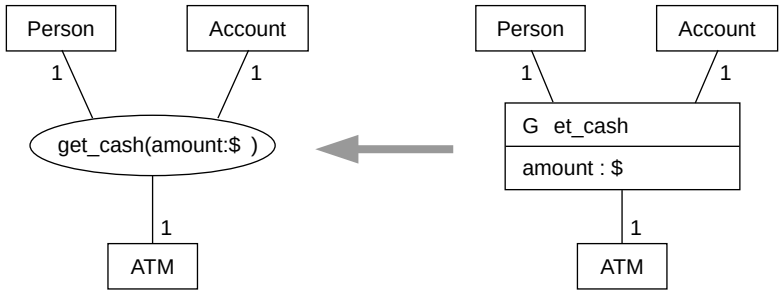


Figure 6.28 Reification of get_cash action.

6.28). As we add detail about the constituent actions, the extra information is added to this object. The state diagram we drew—depicting the correspondence between the abstract and detailed actions—becomes the state chart of this object.

6.5.5.2 Action Refinement and Design Layers

The relationships between abstract actions and their more-detailed constituents cover a scale from individual keystrokes or electrical signals to large-scale operations. The objects that reify these actions range from GUI controllers to entire application programs. For example, the operations of editing words and pictures in a drawing program can be seen as refinements of the overall action of creating or updating a document; the in-memory version of the document, and mechanisms such as the cursor and scrollbars, are part of the extra information attached to the object at the more detailed level. At an even bigger scale, workflow and teamwork systems help control the progress of a project through many individual tasks, with documents as intermediate artifacts.

Within a software design, the different levels of refinement are generally associated with different, decoupled layers in the software. We can see this, for example, in the conventional separation into business and GUI layers. We can also see it in communications protocols, from the individual bits up through to the secure movement of files and Web pages.

6.5.6 Action Conformance and Collaborations

We have seen how a more detailed static model is required to describe a more detailed action. The purpose of a model is to carry the effects of one action across to the next; there wouldn't be much use in using a different model for every action. A collaboration is a group of actions and the model that describes them (see Section 4.6).

Because we refine the model with the actions, we usually refine a complete collaboration together: first the model, according to the rules of model conformance, and then each action (see Figure 6.29). Each of the more-detailed actions can be used in several of the more-abstract actions.

Invariants are attached to collaborations or types and govern the actions that are part of the collaboration or the operations that are defined for the type. An invariant says, "If this is

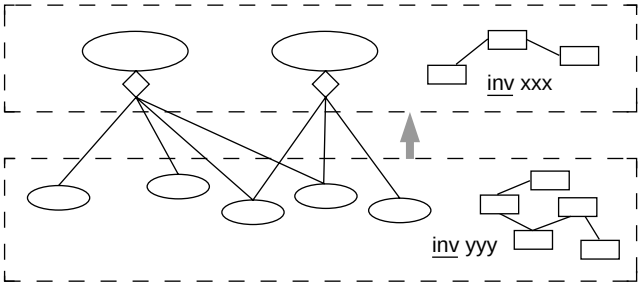


Figure 6.29 Collaboration conformance.

true when we start, it should still be true at the end." It can be conjoined with every pre- and postcondition of every action in its collaboration.

The actions in a collaboration do not observe the same invariants as the actions they refine. For example, when we look at a transaction between a shop and a customer at abstraction sufficient to see purchases, we believe in the invariant that the amount in the vendor's till plus the value of the stock should always add up to the same amount: Every sale simply swaps some stock for some money. But when we look in more detail, we can see that the money is transferred separately from the goods, so there are periods between payment and delivery when the invariant is not observed. Nevertheless, this layer still has its own invariants—for example, that the total of the vendor's and the customer's cash is always the same.

Therefore, invariants should always be quoted as part of a given type or collaboration. Before doing anything to correlate one level of abstraction with another, absorb the invariants into the pre- and postconditions.

6.5.7 Action Conformance within Software

Action refinement is not solely about user interactions. You can use the same principle when describing dialogs between objects in the software. This lets you describe collaborations in terms of the effects they achieve before you go into the precise nature of the dialog.

For example, one of the invariants of the spreadsheet implementation is that the value of a Cell_t with a sumpart is always the sum of sumpart.operands. To achieve this, my design makes each Sum register as an observer of its operand Cells. When any Cell's value changes, it will notify all its observers; Sums in turn notify their parent Cells. The effect is to propagate any change in a value.

We can document that requirement while deferring the details of how the change is propagated. Does a Cell send the new value in the notify message? Or does it send the difference between old and new values? Or does it send the notification without a value and let the observer come back and ask for it? In the midst of creating the grand scheme of our design, we don't care: Such details can be worked out later, and we want to get on to other important issues first. The art of abstraction is about not getting bogged down in detail!


```
-- for any action on Cell
inv effect Cell:: update_when_change
post     -- if its value changes, every sum using this cell as an operand is updated
     value <> value @ pre ==> ~ operands->forAll (s | (self,s).update ())

action (c: Cell, s: Sum) :: update
   -- the change in value of cell is propagated to the sum
   -- we have not said what the protocol is for accomplishing this update
   post
   c.value – c.value@pre = s.~sumpart.value – (s.~sumpart.value)@pre
```

Figure 6.30 Deferring the update protocol.

All we need do at this stage is to record the relationship and the effect it achieves. For this, we use an invariant effect that constrains all (see Figure 6.30).

6.5.8 Action Conformance: Summary

Actions are used to describe the way in which objects—people, hardware, or software—collaborate. Actions are primarily described by their effects on the participants and secondarily as a series of steps or another refinement to smaller actions.

Action abstraction allows us to describe a complex business or software interaction as a single entity. Action refinement can be traced all the way from business goals down to the fine detail of keystrokes and bits in wires.

A useful technique in documenting action conformance is to draw a state chart of the progress of the abstract action through smaller steps.

6.6 *Spreadsheet: Object Refinement*

Object conformance means recognizing that a particular single object is an abstraction representing several constituent parts and that the state and responsibilities attributed to the abstract object are in fact distributed between the constituents.

Object conformance often accompanies action conformance when it turns out that the detailed dialog is not conducted between the participants as wholes but rather between their parts. You can get cash from a bank, but more specifically from one of its cashiers or ATMs. In fact, looking at the actions in detail, when you receive cash from an ATM it actually comes from its money dispenser.

In Catalysis, we separate the act of writing the requirements of a system from the act of designing the internal messages that deal with each action. In requirements specs, we treat the system or component we're designing as a single object. The closer inspection of a system to treat it as a set of interacting objects is only one example of object refinement.

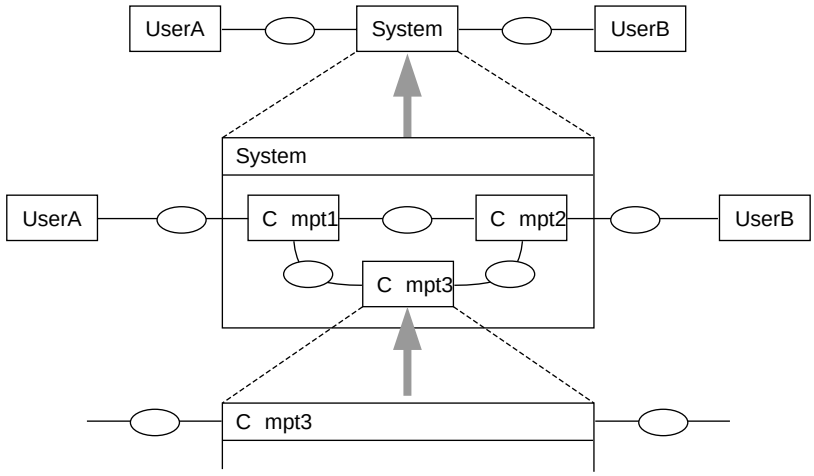


Figure 6.31 Fractal process of refinement.

The process can be fractal: Like all our techniques, it applies as well to a complete system as to a small object inside the software (see Figure 6.31). A system design can start by refining into major components and then can define the high-level actions between them. Subsequently, those actions can be refined to provide more interactive detail. Each component can itself be refined into constituent objects and so on, until the actions are individual messages, and the objects are things you can write directly in your favorite programming language.

Looking in the other direction, the system we're interested in designing is part of a larger machine or organization or software system. By zooming out, we can understand better how our design will help fulfill the overall goals of the larger object.

This section uses the term *component* to refer to the object we are interested in refining, but the same principles apply on every scale.

6.6.1 What an Object Means and Doesn't Mean

We can use an object to describe any concept, including the active components of a system, whether people, hardware, or software or groups or parts thereof. Similarly, we can use a type to describe the behavior of such objects and use actions to describe its participation in interactions with other objects.

A type always describes the behavior of a linked-together collection of smaller constituents. A closer look reveals the parts and reveals that different parts deal with different behavior.

To specify the abstract object's behavior, we use a type model that tells us nothing about the abstract object's internal structure. The internal structure can be described as a set of linked objects participating in actions; the actions occur between the objects and with the outside world. A more detailed picture that reveals the internal structure must

account for how the external actions visible in the abstract view are dealt with by the internal structure.

6.6.2 The Process of Object Refinement

The kinds of refinement we've already looked at can be used in a variety of ways, but they fit together particularly well as part of an object refinement. So let's review those techniques as steps forming part of object refinement.

We've looked at this process in other parts of this book. The point here is to see the steps in terms of the formal refinements defined in this chapter.

6.6.2.1 Start with the Specification

The model we begin with specifies the behavior of our component. Most objects are involved in more than one action: Our spreadsheet has addOperand, setNumber, and so on. Some objects are involved in actions with several other objects: Whereas the spreadsheet has one user, the bank's ATM has customers, operators, and the bank's host machine to deal with. Each of the actions can be specified at a fairly high level, with details to be worked out later (see Figure 6.32).

For each action, we have a specification, in terms of more-or-less rigorously defined pre- and postconditions (and possibly rely/guarantee conditions). Given this context, we work out which objects there are inside our abstract object and how they collaborate to

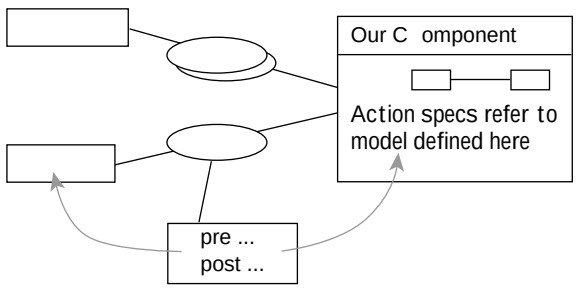


Figure 6.32 Joint action specified in terms of multiple participants.

achieve the effects specified for each of the abstract object's actions.

Notice that we might be refining only one of these objects; perhaps the others are users whose behavior is the province of the GUI designer and the manual writer. Or it might be that we will be refining several of them if they are components in a larger system.

6.6.2.2 Design the Object Model

The actions are specified in terms of their effects on the participants, of which our component is one. For that purpose, each participant has a model. For simple objects, it may be

only a few attributes; for complex ones, it will be a picture based on the business model. Our spreadsheet has cells and their various contents.

Focusing on the system we're interested in refining (the spreadsheet rather than the user), we may decide, as we did in this example, to use a different set of objects in the actual design. We have already seen how to use abstraction functions to relate the design model to the specification.

6.6.2.3 Refine the Actions and Mask the Specs

We refined the actions (so that setSum became <setAddition, addOperand>) and specified the more-detailed versions in terms of the design model (C ell_I rather than C ell and so on).

At this stage, we *mask*: remove anything from the action specs that talks about the other participants in the actions. For example, we don't care about the state of the ATM user's pocket as long as the ATM dishes out the cash. In the spreadsheet example, we didn't say much about the user's state anyway. In an action involving two or more software components, the team working on each component would make its own version of the action spec that would define only its effect on the team's component.

In some cases, masking is easy: The postcondition says, oneParticipant.someEffect AND theOtherParticipant.someOtherEffect We simply throw away the clauses that don't apply to us. The other components' teams will worry about them.

Sometimes the postcondition is written so that the effect on our component depends on something elsewhere. In the ATM, for example: "IF the account in the user's bank is in credit, THEN the user gets the money." This means that, in refining the action, we must include an action with the user's bank that transfers that information here. (This also applies to preconditions, which are equivalent to an *if* clause like this.)

Masking should also make the actions directional, with a definite initiator and receiver, so that they are more like messages. However, they may still encapsulate a dialog refined later. This approach enables us to summarize the component spec in the form of a type diagram with model and action specifications (see Figure 6.33).

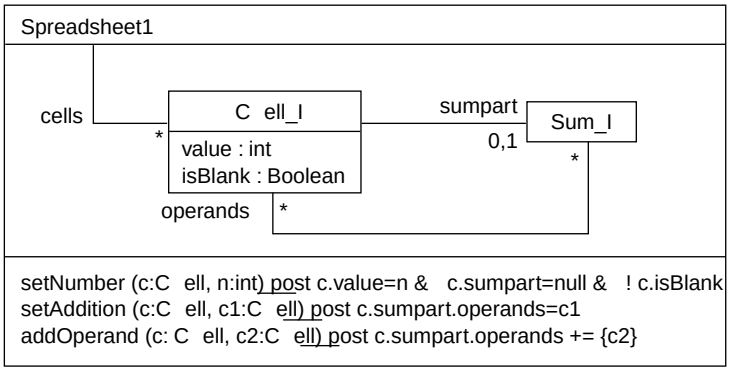


Figure 6.33 Localize and specify actions.

We refine the actions down from the highest-level business abstractions but not down to individual keystrokes or electrical pulses. We refine actions to the point where they make sense as individual actions on the objects we have chosen for our design—if you like, to the same conceptual layer as our design. "Make a spreadsheet" is too abstract for our design; "click mouse at (x,y)" is too detailed; but setNumber(n) makes sense as a message to one of our cells.

All such judgments are relative. Working in the GUI layer, mouse clicks and keystrokes are what we deal with, and the job is to parse them into actions that can be dealt with by the spreadsheet core. Working in a workflow system, the creation of a spreadsheet might be only one action, so that, from its point of view, the spreadsheet program is all a detail of the user interface that builds a series of cell-setting operations into one spreadsheet creation. A good guideline is this: "What would constitute a useful unit of work for the client?"—something the client would cheerfully pay for.

6.6.2.4 Localize Each Action to a Constituent Object

We now make each action the prime responsibility of one of the design objects internal to our component. Usually, a good choice is the proxy object that represents the external participant of the action, which might be a user, a piece of hardware, or a software object in a different component. If there is no such proxy—as in our spreadsheet, which has no representation of its user—then one of the action's parameters is the next choice. We'll choose the target Cell. (In any case, a proxy often just sends the message to one of the parameters. But there is good pattern in which all messages to and from an external object should go through their local proxy, which thereby keeps abreast of what its external counterpart is up to.)

With the assignment of a component action to one of its constituents must, of course, go the specification of what it is supposed to achieve.

6.6.2.5 Operation Refinement for Each Component-Level Action

Now we work out how each component-level action is dealt with by the object it is assigned to—in other words, we design the sequence or write the operation code so as to meet the spec. Typically, this means sending messages to other objects.

We could put it more generally and say that each object can initiate actions with one or more other objects. You may know what you need to achieve and who should be involved, but you may not care (yet) how it is to be achieved or who should be primarily responsible for each part.

The receiving objects must themselves be designed, so they then pass messages to other objects. The result is that many of the component's internal objects now have their own specified actions.

We repeat the procedure for each of the component-level actions. The component's responsibilities are now distributed among its constituents. This is the essence of object refinement.

6.6.2.6 Visibilities

One last step is to decide who can see whom—in other words, object attributes—and we append arrowheads to the links in our model. The simple criterion here is that any object needs a state corresponding to a link to every other objects that it must "remember" across its operations. Again, these links need not correspond to stored pointers in program code; they can themselves be abstractions subject to further refinement.

In some cases, each object of a linked pair must know about the other. This in itself can add some final operations relating to the management of the link. An important pattern is a *two-way link*. When two objects refer to each other, it is important that they not get out of sync and point at different objects or point at a deleted object. Therefore, the only messages that immediately set up or take down the link should come from the object at the other end. When an object wishes to construct a two-way link with another object, it should set its own pointer and then register with the other. (See Pattern 16.14, Two-way link.)

6.6.3 Documenting Object Conformance

Interaction diagrams (also called object interaction graphs or OIGs) are snapshots with messages added. They are useful for illustrating particular cases. One or more collaborations can be drawn for each component-level action.

For example, our spreadsheet C ell will respond to an addOperand by sending the message to its Sum, which will set up an observer action with the target C ell (see Figure 6.34). The diagram shows the new links and objects in bold. A new observation relationship is created; It is an ongoing action characterized by its guarantee rather than its postcondition. It is treated as an object in these diagrams. We have decided that, at this stage, we don't care how it works, although we will specify what it achieves.

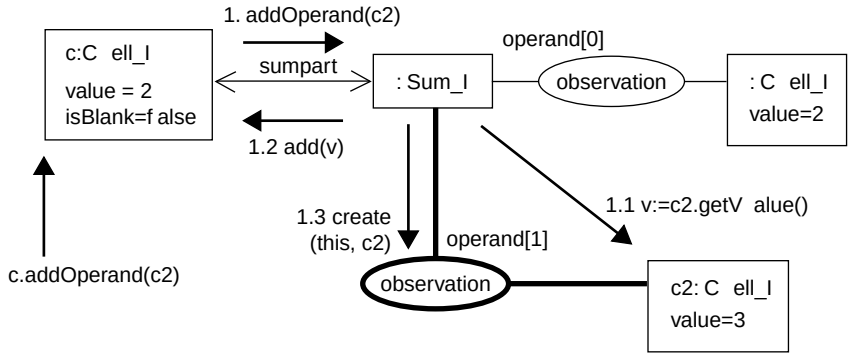
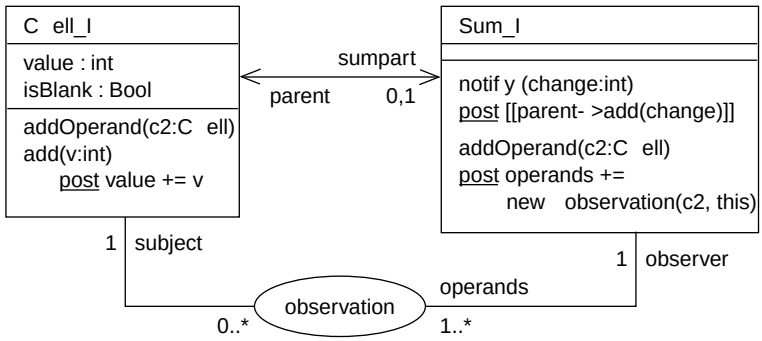


Figure 6.34 Internal interactions in the spreadsheet.

As is often the case when working out an interaction, we find we have brought new elements into the design. These elements should now be incorporated into the class diagram

and specified. At the same time, we can begin to add localized actions to the classes (see Figure 6.35). (Recall that the [[action]] notation is used within a postcondition to specify that another action has been performed as part of this one.) We have specified the observation action; it may become an object in its own right or (more likely) will turn out to be only a contractual relationship between its participants.

Notice that although the interaction diagram is useful for illustrating specific cases, the class diagram (with associated dictionary, specifications, and code) is the canonical




```
action observation
guarantee subject.value <> subject.value@pre. ==>
          [[observer- >notif y(subject.value- subject@pre.value)]]
          -- whenever the value of the subject changes, the difference
             will be sent to the observer using the notify message
```

Figure 6.35 Update class diagram with localized actions and specs.

description of the design. As more collaborations are drawn, more detail can be added to the class diagram. Ultimately, we must also resolve observation to specific messages and attributes.

A sequence diagram is an alternative presentation of the same information as shown in a collaboration diagram and is better at showing the sequence of events; but the collaboration diagram also shows the links and objects. As an example, Figure 6.36 shows the sequence of the propagation of changes.

6.6.4 Object Access: Conformance, Façades, and Adapters

How do the external objects get access to the appropriate constituent objects within our component? The following sections discuss how access is implemented.

6.6.4.1 Direct Access

If the external objects and our component are all in the same body of software, there is a straightforward answer: All of them have references to those of our constituents they want to communicate with. When we do an object refinement, the main task is to work out how

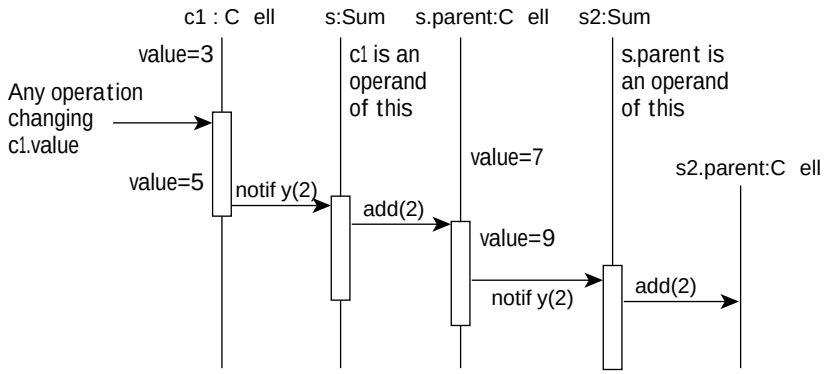


Figure 6.36 Sequence diagram alternative.

the externals will initially connect to the appropriate internal. Our abstract component object is a grouping of smaller objects, and we allow the boundary to be crossed arbitrarily (see Figure 6.37).

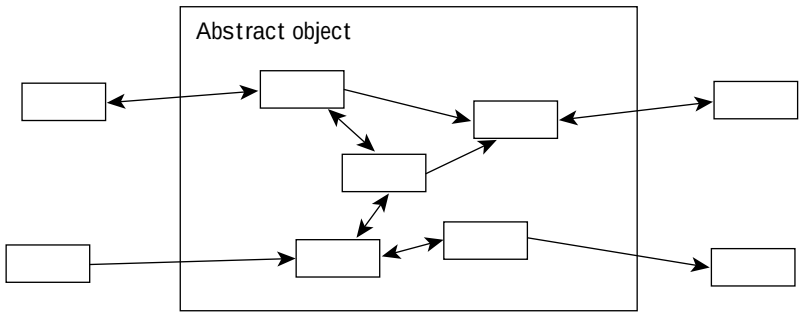


Figure 6.37 Direct external access to internal objects.

There can be a variety of drawbacks to the direct access scheme: making it more difficult to guarantee abstract object invariants and exposing more of the internal design decisions than necessary. Each of them applies only in certain circumstances.

6.6.4.2 Façade

A façade is a single object through which all communication to a component flows. It simplifies several aspects of object refinement.

• You need not design the external objects to know which constituent to connect to. In the direct access scheme, refining our object also means designing the externals to work with our organization.

A business analogy is a company that provides a single point of contact for each customer or supplier. It saves the outside entity from having to understand the company's

internal organization.

A corollary is that, if the design of the external objects is already finalized, a façade is necessary.

• Invariants applying to the component as a whole can be supervised by the façade, because it is aware of every action that could affect it. Conversely, the external objects have no direct access to any objects inside.

The supervision of invariants is a common motivation. Consider, for example, a SortedList object, in which the members of the list are NumberContainers; the value of a NumberContainer can be changed by sending it an appropriate message. The documented invariant of SortedList is that its members are always arranged in ascending order. But if external objects have direct access to the list's members, they can sneakily disorder the list by altering the values without the knowledge of the anchor SortedList instance.

Making the façade the only way of accessing the list elements is one way to keep control. The other approach is to implement a more complex Observation scheme whereby the elements notify the façade when they are changed.

A single façade can, however, be somewhat limiting. Every change to the internal objects to add or change the services they offer to the outside requires a corresponding change to the single façade even if particular clients never see that service.

6.6.4.3 Multiple Façades

The big drawback of a single façade object is poor decoupling: as soon as you change or add to any of the types in the component, you must extend the façade to cope with the new messages.

However, we can make the façade itself an abstract object consisting of a collection of *peers*: smaller façade objects, each of which handles communication with a given class of internal object. Most GUIs are constructed this way. Corresponding to each spreadsheet Cell, for example, is a CellDisplay object that deals with position on the screen and appearance and also translates mouse operations back to Cell operations.

In a more general scheme, different categories of external objects may have different *ports* through which to gain access, each of them a different façade.

6.6.4.4 Adapters

It's easy to draw links and messages crossing the boundary of a component; but what if the objects are in different host machines or written in different languages? Or what if the external objects are machines or people? How do the messages cross the boundary, and what constitutes an association across the boundary?

These objections are met by building an appropriate *adapter*: a layer of design that translates object references and messages to and from bits on wires (such as CORBA); or to pixels and from keystrokes and mouse clicks (the GUI). An adapter is a façade with strong translation capabilities.

Typically, you deal with references across boundaries by mapping strings to object identities. Your bank card's number is the association between the physical card and the

software account object in your bank's computer; the spreadsheet cells can be identified by their row-column tags. The other common method is by mapping screen position to object identity, as when you point at its appearance on the screen.

It is because of the adapter(s) that we can always begin the object refinement by assuming that the appropriate internal object will be involved in the external actions. We leave it up to the adapter design.

In the case of the spreadsheet, a considerable GUI will be required to display the spreadsheet, to translate mouse operations into the specified incoming messages, and to direct them to the appropriate cells.

6.6.4.5 Boundary Decisions in Object Refinements

Object refinements, whether on a small or large scale, always involve a decision about how the boundary is managed: whether direct access is OK or whether a façade or the more general adapter layer is required.

Our original picture of an object refinement as a simple group of objects has now become a group of objects plus a layer of adapters (see Figure 6.38).

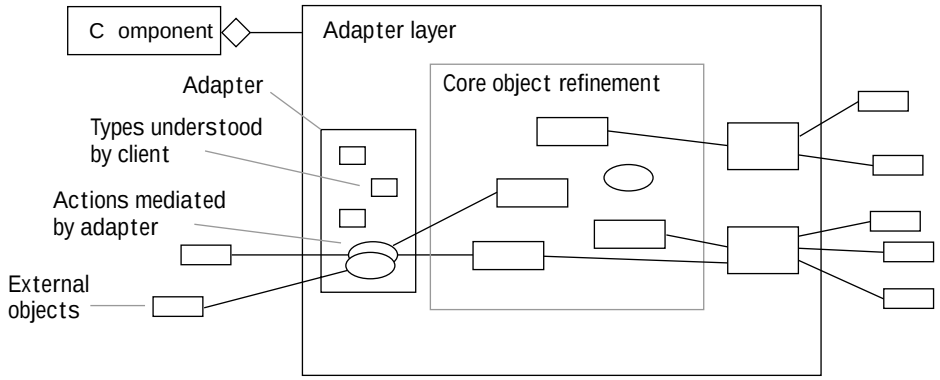


Figure 6.38 Object refinement with adapter objects.

6.6.5 Object Conformance: Summary

Object abstraction gives us the ability to treat a whole collection of objects—people, hardware, software, or a mixture—as a single thing with a definable behavior. This can be applied on the large scale of complete computer systems and businesses or on the small scale such as software sets and lists.

The key to documenting conformance is to show how the responsibilities of the abstract object are distributed to its constituents.

6.7 *Spreadsheet: Operation Refinement*

Operation refinement means writing a program that fulfills a given pre/post (and/or rely/guarantee) specification. It is here that we finally get down to program code. In one sense, this is the part we need to say least about, because the point of this book is not to teach programming; you know how to put together loops and branches and sequences and can easily learn any (far more verbose) graphical representations of the same. However, there are some special considerations, most of them about decoupling, which is what OO programming is all about.

6.7.1 What Operation Abstraction Means and Doesn't Mean

An operation is a subtype of an action: operations are actions consisting of an invocation from a sender to a receiver, followed by an activity on the part of the receiver and possibly ending with a return signal to the sender. Operations are a one-sided view of the sender-receiver interaction.

If an operation is invoked in a situation when the precondition is false or if, during the execution of the operation, its rely condition becomes false, then the specification does not state what the outcome should be.

If an operation is invoked in a situation when the precondition is true and the rely condition is true throughout, then, by the end of the operation, the postcondition will have been achieved; and during the execution of the operation, the guarantee condition will have been maintained.

Preconditions and rely conditions, by default, are "true" and there is no obligation on the sender. Similarly, an empty postcondition or guarantee condition imposes no obligation on the implementor.

The operation should not alter variables that could be left untouched while achieving the postcondition and guarantee conditions.

Any invariant in the model should be considered to be ANDed to the pre- and the postconditions (but not the rely and the guarantee conditions).

6.7.2 Strong Decoupling

In conventional programs, you split a big program into subroutines so that common routines can be invoked individually and so that the program is easier to understand. In OO programming, the process goes even further. For every statement, you think, "Which object should this be attached to? Which object has the information and the other operations most strongly relevant to this?" Then you send a message to the appropriate object. Actually, that's not for every statement; rather, it's for every subexpression.

The purpose is to ensure that the program is well decoupled. If the preceding stages of design have gone well, many of these questions should be sorted out. However, you defi-

nitely have more decisions to make in an OO development than in procedural development.

The choice of types for a local variable—temporaries, inputs, and even return values—for an operation is crucial to good decoupling. As soon as you declare a variable or parameter that belongs to a particular class, you have made your part of the program dependent on that class. This means that any changes there may have an impact here. Instead, it is usually better to declare all variables as *types*; the only place in a program where you absolutely must refer to a concrete class is to instantiate a new object.

There is a variety of powerful patterns to help reduce dependencies.

• *Role decoupling:* A variable or parameter contains an object or a reference to one. Frequently, the component in which the declaration occurs uses only some of the facilities provided by that object.

Therefore, define a type (that is, an interface or pure abstract class plus a specification) that characterizes only the features that you will use. Declare the variable to be of this type. Declare the object's class to be an implementor of this type. This approach will minimize the dependency of your component on the other object. Related patterns are adapter and bridge [Gamma94].

(Role decoupling is particularly important for two-way links.)

• *Factory:* An object must be created as a member of a definite class. This gives rise to a dependency between your class and that one.

Therefore, devolve to a separate class the decision about which class the new object should belong to. By doing this, you encapsulate the class dependency behind a type-based creation method [Gamma95].

6.7.3 Documenting Operation Spec Conformance

Whether we have written it informally or in more precise form, we should have a specification of what is expected of each operation. We should attempt to check that the program code of each operation conforms to what is expected of it.

The most reliable method is to turn the specs into test harnesses, as we discussed earlier. But there is also the Deep Thought approach: as a general principle, it is possible to inspect both specification and code and to check that one meets the other by a judicious mixture of careful reasoning and guesswork. Although Deep Thought is not an economical method of verification outside safety-critical circles, being aware of the basic principles can help anyone root out obvious mistakes before getting to the testing stage.

There are two ways of fulfilling a spec. The hard way is to write the entire implementation yourself. The easy way is to find something that comes close to already doing the job and possibly bend the requirements to suit what you've found. The latter is usually more economical if you're fairly confident of its provenance and integrity (see, for example, Section 10.11, Heterogenous Components).

6.7.3.1 Comparing Two Operation Specs

Suppose we find some code in a library and we suspect that it does the job we require. Miraculously, it comes with a spec and model of some sort, which we want to compare to our requirements spec.

The rules for comparing two pre/post specs are as follows.

- Any invariants in each model should be ANDed with both pre- and postconditions written in that model.
- If the requirement has several pre- and postcondition pairs—which may come from different supertypes—they should be ANDed in pairs ((pre1=>post1) AND (pre2=>post2)) to give an overall requirement postcondition. If the pre- and postconditions are not from supertypes and are subject to joining (see Section 8.3.4, Joining Action Specifications), compose them accordingly.
- The implementation's vocabulary should be translated to the specification's by using retrieve functions as in Section 6.4, Spreadsheet: Model Refinement.
- The precondition of the requirement should imply the precondition of the implementation. For example, if the requirement says, "This operation should work whenever Cell c contains a Number," then an implementation that works "whenever c is non-Blank" is fine because it is always true that "a Cell contains a Number => it is not Blank."
- The postcondition of the implementation should imply the postcondition of the specification. (Notice that this is the other way around from preconditions, a feature called *contravariance*.) So if the implementation claims that "this operation adds 3 to the Cell's value" whereas the requirement is more vague ("this operation should increase the Cell's value"), then we are OK, because it is always true that "3 added to value => value increased."

6.7.3.2 Comparing Operation Specs with Code

More likely, you will have to compare your specification with code (whether you've written it yourself or someone else has). Again, the most effective strategy is to write test harnesses, as we discussed before.[8]

In debug mode, preconditions should be written as tests performed on entry to an operation; postconditions are tested on the way out. The only complication is that, because postconditions can contain @pre, you must save copies of those items while checking the precondition. (Or you may be lucky enough to be using a language with this facility built-in.) The main caveat is to ensure that the pre- and postconditions don't themselves change anything.

If you prefer the Deep Thought approach, many (unfortunately, rather academic-sounding) books have been written on how to document this kind of refinement (for example, [Jones] and [Morgan]). The following summarizes the key points in a pragmatic way.

8. For more on the Deep Thought approach, see [Morgan88] or [Jones86]. For more on executing pre- and postconditions, see [Meyer88].

- For sequences of statements separated by a semicolon (;), it is useful to write assertions (conditional expressions that should always be true) within the sequence. This helps you see how the requirements are built up with each statement and can be a useful debug tool if the expressions are actually executed. The assert macro provided with C++ has parallels in other languages.
- Where an operation is called within a sequence, its precondition should be satisfied by the assertion immediately before it; the assertion after it should be implied by its post-condition.
- If statements ensure preconditions for their branches. The postcondition of the whole thing is an OR of the branches:

```
if (x>0) z= square_root(x)          // pre of square_root is 'x>=0'
    else z=square_root(–x);
assert z*z == x  or  z*z == –x
```

- In a loop, it is useful to find the loop invariant: an assertion that is true every time through the loop. It works as both pre- and postcondition of the body of the loop. Together with the condition that ends the loop, it ensures the required result of the loop. For example, consider this routine:

```
post sort queue into order of size
{   int top= queue.length;
    w  hile(top > 0)
    invariant everything f romtop to end of queue is sorted,
    //    and everything before top is smaller than everything beyond top
    {     post move biggest of items f rom0 to top along to top
          { ... to be w  ritten.. }
          top = top –1;
    }
    // top == 0 and everything from top to end of queue is sorted
    }
```

Here, the invariant separates the queue into two parts: unsorted and sorted. The top pointer moves gradually downward, until the whole queue is in the sorted part.

If you were called to review such a refinement, you should check that (1) the claimed invariant is bound to be satisfied on first entry to the loop (it is satisfied here, because there's nothing beyond top); (2) if the invariant is true before any iteration of the body, it is bound to be true after; (3) the invariant and the exit condition together guarantee the effect claimed for the whole thing (true in this case because when top gets to 0, the whole queue must be sorted).

Notice that a postcondition has been written to stand in for a chunk of code not yet finished; we are simply using known techniques to defer details, except that now we're using them in code. (How would you design it? What would be the loop invariant?)

6.7.3.3 Operation Conformance and Action Conformance: Differences

Both operation and action conformance show how a single action with an overall goal is released by a composition of smaller actions, and some of the techniques for establishing the relationship are the same. The differences are summarized in Table 6.2.

6.7.4 Operation Conformance: Summary

Operation abstraction makes it possible to state what is required of an object without going into the detail of how the requirements are met. The implementation will use whatever constructs are provided by the programming language, such as sequences, branches, and loops; it will choose its own set of variables and stored data. There are well-defined rules for verifying that the implementation meets the specification or, more pragmatically, systematic techniques for instrumenting and testing the implementation.

Table 6.2 Operation Conformance versus Action Conformance

Operation Conformance	Action Conformance
An operation begins with an invocation: a function call or message send. This prescribes the limits on the sequence of events that should happen. We know from the beginning of the sequence which operation we're dealing with	An action is identified only in retrospect. If someone selects some goods in a shop, it will often be the first step to a sale; but the shopper might decide not to buy or might walk off without paying; so it turns out not to have been a sale but a theft. An action is a name for an effect. We can provide a protocol of smaller actions whereby it can be achieved, but the same actions may be composed in some other way to achieve something different.
When we design a procedure that refines an operation spec, we can focus on the receiving object and devolve subtasks to other objects we send messages to. If we change the design, we are changing this one object.	When we design a protocol of actions that satisfies an action spec, we focus not on any one participant but on the interactions between them. If we change the refinement, we affect the specs of all the participants.
Refining an operation is like designing a computer monitor: You have the specs of the signals that come along the wires and their required manifestations on the screen. Your work is to define the insides of the box; you may involve others by specifying parts you will use inside. Your design talks about the specifications of the constituent parts and how they are wired together.	Refining an action is like devising an interface standard for the signals on a video connection. You must involve all the designers who might make a box to go on either end of this connection—or at least all those you know at the moment. You must agree to a specification for what is achieved and then refine it to a set of signals that, in some parallel or sequential combination, achieves the overall required effect. You cannot talk in terms of any thing inside the boxes, because they will all be different; you can only make models that abstract the various boxes and talk in terms of the signals' effects on them.
To test an operation refinement, you push a variety of signals in, from different initial states, and see whether the right responses come out. There are various ways to use a precise specification to generate test cases that reasonably cover the state space of input parameters and initial state.	To test an action refinement, you must see whether it permits a variety of different combinations of participants to collaborate and achieve the desired effect. Interoperability is the general goal. The goal here is to explore each sequence of refined actions that should realize the abstract one—a much larger, sequential state space. Scenarios defined during modeling form a useful starting point; the specs can be used to systematically get broader coverage than just the scenarios.

6.8 *Refinement of State Charts*

In the Catalysis interpretation, the states in a state chart are Boolean conditions and the transitions are actions. As such, actions may take time; there is a gap between one state going false and the next state lighting up (rather like the floor indicator in many elevators).[9] Most state charts focus on a given type, and the states are defined in terms of its attributes.

A Cell can contain a Blank, a Number, or a Sum. Let's consider the abstract setSum action, which should set the target cell to be a sum of two others, shown on a simple state chart in Figure 6.39. We would have to wait for the user to enter two operands before the transition to a Sum was completed. During the interval, the implementation is in no state

Figure 6.39 Intermediate states due to refinement.

that the abstract spec understands. The addition of the intermediate state is a valid change specifically in a refinement.

Each state in a state chart should be documented with a condition stating when it is true. In this case, isBlank corresponds directly to the attribute of that name; isSum == (content : Sum) ("the content attribute is of type Sum").

Because states are Boolean attributes, retrieving a state is no different from retrieving any model. The abstract states can still be seen in the refinement, although you must use the abstraction functions to translate from sumpart to content (Figure 6.20). Also, the extra state must be given its own definition.

6.8.1 Distinguishing States of Spec Types from Design Types

Considering the GUI for a moment, it may be useful to make a small state chart about whether or not a Cell is selected (see Figure 6.40). The Cell type forms part of the spreadsheet's model; the actions are those of the spreadsheet as a whole (see Section 3.9.4, State Charts of Specification Types). The states diagram applies simultaneously to every Cell in the model. Any Cell that is the subject of a select operation gets into the selected state; all others go into unselected, as defined by the guard.

To accommodate the new bit of information, we could add an optional link to the model. It is then easy to write a definition for the selected state (see Figure 6.41). Now, when we come to the implementation, the pointer to the currently selected Cell comes from somewhere in the GUI, and, because the pointer is one-way, the Cell itself does not know that it is selected. (In fact, it would be common in an MVC design for the implemented cell to remain unaware of many such changes in UI state.) Is the original state diagram still valid if the Cell has no information about its state of selection (see Figure 6.42)?

9. We prefer our state charts like this, because they are easier to reconcile with the actuality of the software compared with *instantaneous event* models; and they tie in better with the actions. In some notations, they would have an event representing the start of an action and another for the end of it, and a state in between representing the transitional period. But at a given level of abstraction, we do not know enough to characterize the intermediate state, because that is defined only in the more-detailed layers of the model.

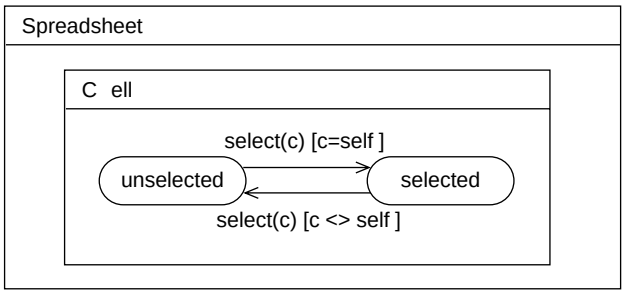


Figure 6.40 Cell selection state chart.

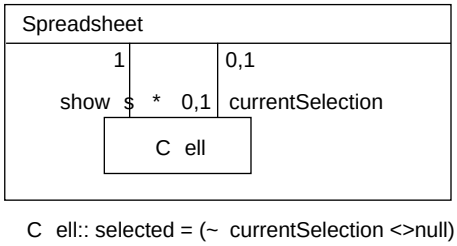


Figure 6.41 Link for indicating cell selection.

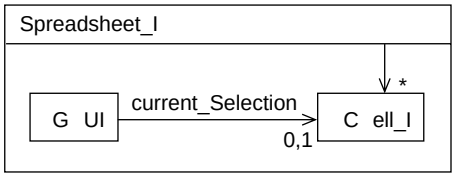


Figure 6.42 Implementation: Does a cell still have a "selected" state?

Yes, the state diagram is valid. For one thing, the state diagram is of a C ell and not a C ell_I and the abstraction function to Spreadsheet from Spreadsheet_I should yield all the information about each C ell. In any case, it would still be valid to draw that diagram for a C ell_I. We need only define the state with a little more imagination—something like this:

```
C ell:: selected = (there is a Spreadsheet_I si, for which
                    si.gui.current_selection = self )
```

The there is means in practice that you must search around the object space until you come to a Spreadsheet and try it for that property; but we said that specification functions need not execute efficiently to be meaningful.

6.8.2 Other State Chart Refinement Rules

If your project uses state charts extensively, you may wish to look at {Cook94], where a complete set of rules for refining state charts is provided.

6.9 *Summary*

The various kinds of abstraction make it possible to discuss the essentials of a specification or design without regard to the details and to define systematic approaches to verifying that an implementation does what it is supposed to do.

Catalysis provides a coherent set of abstraction techniques and also provides the rationale to relate more-detailed accounts to the abstractions and to document the conformance with specific descriptions.

The justification associated with a refinement can be formal or informal; it could even simply say, "Joe said this will work." The verification techniques can be applied in varying degrees of rigor, from casual inspection to mathematical proof. In between, there is the more cost-effective option of making refinements the focus of design reviews and basing systematically defined test code on the specifications (see Figure 6.43).

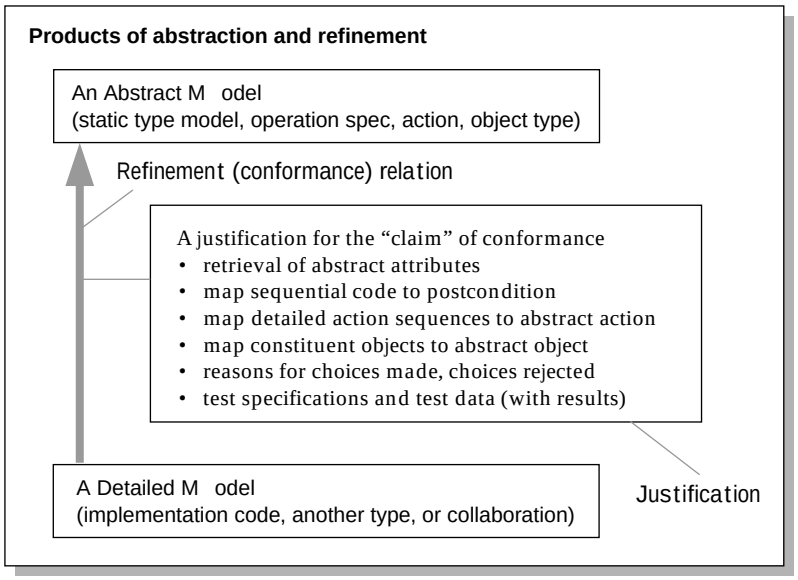


Figure 6.43 Refinements and justifications.

6.10 *Process Patterns for Refinement*

Following is a set of high-level process guidelines for applying refinement techniques.

- *Pattern 6.1, The OO Golden Rule (Seamlessness or Continuity)*: This shows how to achieve one of the most important benefits of objects: a seamless path from problem domain to code.
- *Pattern 6.2, The Golden Rule versus Other Optimizations*: This is the pattern to use when stringent requirements about reuse, performance, or flexibility keep you from maintaining the most straightforward continuity to code.
- *Pattern 6.3, Orthogonal Abstractions and Refinement*: Sometimes the most dramatic simplifications and flexibility come by adopting a whole new view of domain terms (e.g., spreadsheets, cells, and formulas can support accounting, inventory tracking, and baseball scores).
- *Pattern 6.4, Refinement Is a Relation, Not a Sequence*: Do not make the common mistake of thinking that refinement means top-down development; it is a fundamental relation between different descriptions regardless of which one was built first.
- *Pattern 6.5, Recursive Refinement*: The ideas of refinement apply at all levels, from describing organizations and business processes to program code. This means that it can form the single consistent basis for traceability.

Pattern 6.1 The OO Golden Rule (Seamlessness or Continuity)

In ths pattern, you build a system that clearly maps to a model of the problem or real world and keep it that way (also called *continuity* or *seamlessness*).

Intent

An object-oriented design is one in which the structure of the designed system mirrors, to the extent possible, a well-chosen model of the world in which it works. Many of the advertised benefits of object technology come from this principle. It is made somewhat easier because object-oriented languages provide mechanisms that roughly simulate the real world's dynamic interaction between state-storing entities; object technology has strong roots in simulation techniques and languages (such as Simula). Objects have a strong relationship to the artificial intelligence (AI) subculture's *frames*, which are units of an agent's understanding of the world around it.

Considerations

Truth and Reality. You must begin by making a model of the real world. But what does *real* mean?

- One person's view of reality will be different from another's. There are numerous views of reality. Many of them may be self-consistent but may be cast in terms different from those of others. It is important that the model of each class of user be clearly reflected in the system as the user sees and uses it.
- There are numerous ways to use the notation to model the same set of ideas.
- While constructing a model, you will ask and resolve many questions that have never previously been resolved. This is a good thing, but you must be aware that by forcing precise and consistent descriptions of reality you are actually constructing reality and not passively discovering it. And again, the various interested parties will have varying views on what the answers should be.

Compromise with Practicality. The design that mirrors the users' concepts most closely is not always the most efficient, and it sometimes takes significant factoring in design to achieve flexibility. Compromises must be made, and there is an architectural decision about how far to do so. Fortunately, this can be taken to different degrees in different parts of the design; see Pattern 6.2, The Golden Rule versus Other Optimizations.

Strategy

Build and Integrate Users' Business Models. See Pattern 14.2, Make a Business Model. This is always a good starting point. On a typical software project, an astonishing

number of downstream problems can be prevented by clarifying and building a clear vocabulary of the problem domain.

Cast System Requirements in Terms of the Business Model. See Pattern 15.7, Construct a System Behavior Spec. Particularly if the domain model has been clearly defined, system requirements can be discussed, understood, and decided far more precisely.

Choose Classes Based on the Business Model. To maintain traceability, deviations forced by performance, current or planned reuse, and other constraints should be local and clearly documented as refinements.

Maintain Development Layers (Business Model to Code) in Step. This strategy clearly conflicts with the usual short-term imperative of getting changes done immediately and directly in the code; but a clear separation of domain, system, and technology infrastructure descriptions (and code) helps localize changes, and experience shows clear, long-term benefits. Furthermore, because the documents are more abstract as you go up the tree, you come to a point where there is no change. Performance improvements, for example, usually change the code but perhaps not the requirements or the model in which they are expressed; or some design refactoring for reuse and flexibility may have no effect on the external spec, affecting only the refinement and its associated mapping.

Build Many Projects on the Same Model. A problem domain model is useful across more than a single project. But don't take this as a reason for perfecting a model before building your first system; see Pattern 14.2, Make a Business Model.

Benefits

Many of the advertised benefits of object technology come from this pattern.

- The resulting system relates better to the end users because it deals in the terms they are familiar with (assuming a reasonable problem domain model) and traces back to the business tasks they perform.
- Making changes is easier because users express their requirements in terms that are easy to trace through to the model and implementation. In a good problem domain model, things are factored so that common requirements changes do not cause massive model updates; the design should reflect this structure.
- The same business model can be used for many projects within the same business. As a result, more of the code can also be generalized and reused.

Pattern 6.2 The Golden Rule versus Other Optimizations

Consciously tradeoff performance, reuse, and flexibility optimization against entirely seamless design; document a refinement clearly whenever you must stray significantly from a pristine domain model.

Intent

In an ideal sense, the structure of the design could be based directly on a model of the world in which it works (to an appropriate extent). Performance, flexibility, and reuse constraints sometimes dictate against naive continuity, and elements from architectural design down may need to differ from a real-world model. The question is how to balance the goals of seamlessness, maintainability, reuse, and tuned performance.

Considerations

Will the program code be object-oriented? If it is, should we choose the classes directly from the domain model or based on design patterns or following the gut instincts of the project guru?

Mirroring a good model of the world in your code is good for simulations: Every time you change your picture of the world, you can more easily find which parts of the simulation code to change. This is how OOP originated with the Simula language.

The flexibility provided by polymorphism and dynamic binding in an OOP language, combined with a well-factored design, makes it better suited for writing any kind of program whose requirements change regularly—that is, almost all of them. (It's been estimated that 70% to 80% of total spending in a program's life cycle is in the maintenance phase after first delivery.) However, we gain this flexibility at the cost of making many extra decisions about which object should take responsibility for each small part of the job—something that is often not obvious from the problem domain model itself—and at the cost to runtime performance of all those objects passing control to one another. The former can make a difference in initial project development time; the latter can make a big difference in performance-critical real-time control software such as communications or avionics.

Moreover, there is little flexibility and reuse at the level of individual problem domain objects. Each object plays roles in different collaborations; a far more likely unit of reuse is the collaboration or its manifestation as a framework in code (see Chapter 11, Reuse and Pluggable Design: Frameworks in Code).

Code that makes miraculous-seeming leaps from the domain vocabulary into design decisions, even if based on the best gut instincts, will not retain its intended form for long.

Flexibility comes from decoupling: making components independent of one another. Optimization for performance generally means that pieces of code that were ideally decoupled become dependent on one another's details. So the more you optimize, the

more you mix concerns that were independent before. In the extreme, you end up with a traditional monolithic program.

Strategy

Make an early architectural decision about how much you will tradeoff performance, seamlessness, reuse, code flexibility, and so on. If your clients shout for little functional enhancements every day (something that is typical for in-house financial trading software), optimize the underlying communications and infrastructure but leave the business model pristine. But if your software will be embedded in a million car engines for 10 years, optimize for performance.

Eighty percent of the execution is done by 20% of the code. Design your system in a straightforward object-mirroring way and then abstract and re-refine the pieces that are most critical to performance. (Or analyze a prototype and worry about the execution hotspots.) See Pattern 15.12, Avoid Miracles, Refine the Spec.

Buy faster hardware and more memory. They're much cheaper than programmers.

Benefits

An OO program is one that is refined from an OO design. A clearly defined refinement carries a retrieval that relates it to the abstraction even when the design has been optimized from a real-world abstraction.

Pattern 6.3 Orthogonal Abstractions and Refinement

Sometimes the greatest improvements in reuse and flexibility come by adopting a significantly more abstract (or even orthogonal) view of problem domain terms. Use refinement and frameworks so that you don't lose traceability to domain terms.

Intent

Gain flexibility by using orthogonal abstract views of different parts of the problem, but retain traceability to the straightforward domain terms.

Considerations

You get only so much reuse and flexibility by adopting the most straightforward model of the problem domain. The terms have evolved to be specific to that domain and may be inconsistent with terms used elsewhere.

Consider a couple of examples. First, in an application for supporting a seminar business, we need to schedule instructors and rooms for seminar sessions; track customer preferences and trends to better target our marketing efforts; and maintain a stock of course materials, producing new ones as needed. Although we could analyze this problem in its simplest domain terms, there would be much more opportunity for reuse if we characterized the problem in an abstract, orthogonal way as follows: Assign resources (instructors, rooms) to jobs (seminar sessions); track customer trends for different products (seminar topics); and maintain a just-in-time inventory of items (course notes) of our products (seminar topics). Note that our requirements are now much more generic, merely specialized to our domain specifics. (This example is worked out in more detail in Section 11.4.1.1, Combining Model Frameworks.)

Second, in an application for processing credit cards at a gas station, there are many variations in choices (paying outside versus paying inside), in product offerings (optional car wash or discount items), and in sequences of interactions with the user and the remote financial hosts. We could tackle some of this variability by appropriate design of types and class hierarchies; however, we gain the biggest increase in flexibility when we recognize that we should reify the steps in the card processing (product offerings, payment authorization, amount entry) from the sequences in which these steps are executed. If we build an explicit representation of sequencing and other dependencies, we could even use a generic Petri Net interpreter as an abstract machine for handling arbitrary sequences and dependencies.

However, code that makes miraculous-seeming leaps from the domain vocabulary into design decisions, even if based on the best gut instincts, becomes irreversibly deformed by the first few modifications made by a new programmer.

Strategy

Do not lose sight of the domain terms even in your code. Use refinement to maintain traceability even as your code becomes more decoupled and reusable. Wherever possible, recast the problem domain descriptions themselves using these orthogonal and more abstract views; remember, you are actively constructing a model of reality and not passively discovering it. Use frameworks (see Chapter 9, Model Frameworks and Template Packages) to explicitly document the mapping from domain terms to terms and roles in the abstract problem descriptions.

Pattern 6.4 Refinement Is a Relation, Not a Sequence

Use refinement for any combination of top-down, bottom-up, inside-out, or assembly-based development; it does not imply sequential top-down development.

Intent

Refinement results in realistic deliverables for each development cycle depending on what development process is most suited to the project.

Considerations

We have a clear picture of the ideal refinement relations from business model to code. How is this related to the actual series of cycles of the development process on a particular project?

Clearly, there are some dependencies between prior and consequent phases. Even the most unregenerate hacker does not begin to code without at least a vague idea of an objective (well, not many of them, anyway!) .

But it is obstructive to be overly concerned about completing all the final touches on any phase before going forward to the next. It is a well-known demotivator, paralyzing the creative processes, and is often an excuse for people who don't know how to proceed.

But if too much is undertaken without clear documentation of the aims of each phase (as determined by the outcome of the preceding ones), all the usual misunderstandings and divergences will arise between team members and between the original target and the final landing.

In any case, it's an illusion that every design is determined entirely by the requirements. It's often the other way around. When technologists developed the laser, it was not so that they could make CDs. Few of us knew that we needed musical birthday cards before they were provided for us. We build and use what we have the technology for, and this will become increasingly relevant in a world of component-based development.

Strategy

The typical deliverables of a development cycle (see Pattern 15.13, Interpreting Models for Clients) are *not* individual completed documents from the linear life cycle. More usually, they might be first draft requirements; GUI mockup; client feedback; second draft requirements; critical core code version 1; requirements modified to what we find we can achieve; . . .

Get It 80% Right. To avoid "analysis paralysis"—the tendency to want to get a perfect business model, requirements, or high-level design before moving on—deliberately start the next phase when you know its precursor is still imperfect. Move to the next phase as early as you like but no later than when you estimate there's still about 20% to finish. (Per-

sonal wisdom about the exact percentage varies, of course.) The results from the next phase will in any case feed back to the first.

Bottom-up and Top-down Approaches. Our approach to refinement between spec and design (and other layers of documentation) in no way constrains you to begin with the requirements and end with the code. Called upon to write an article, you need not begin at the beginning. Instead, you edit the whole in any order you like as long as it makes sense when you've finished. Similarly, the context of a project may call for a different route through the method (see Section 13.2.1, Multiple Routes through the Method).

In the same way, consider the various documents of a development to be elements in a structure that you are editing (see Figure 6.44). The goal of the project is to fill in all the slots in the structure and make them all consistent when finished. Feel free to begin at the bottom, if appropriate, and don't worry if things get inconsistent en route provided that they come back in line at some planned milestone.

Coding Can Even Help with Analysis. People know what they *don't* want better than they know what they *do* want. (Ask any parent!) When you put a finished system in front of customers, they'll soon tell you what changes they need. And the system will alter their mode of work, so their requirements will change anyway. To circumvent some of this, deliver early a slide show or a prototype or a vertical slice—whatever will stimulate the imagination. OO can be great for this incremental design, but it must be a clear part of the plan.

- What information will be extracted and fed back to analysis from an early delivery? (And how will the information be obtained? Is the planned delivery adequate to expose that information?)

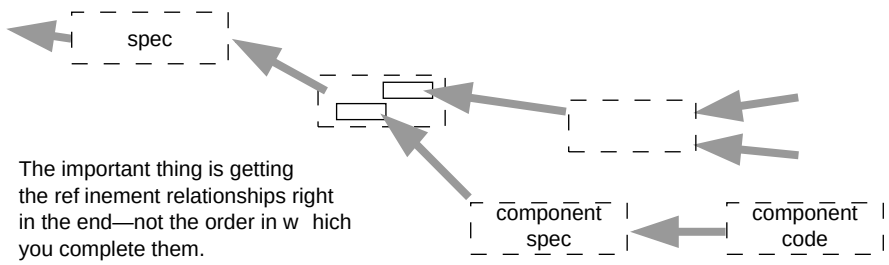


Figure 6.44 Refinement is a relation and not a sequence.

- What will happen to the code? Is it a throwaway? If not, all proper documentation and reviews must be applied. Often, prototypes are not exposed to proper QA—and then are incorporated into the real thing!
- What will happen to the other design documents? The design material usually represents more valuable work than the code itself, so you can build a prototype as a throw-

away even in some other language. This assumes that, as a reader of this book, you're documenting the design in some form other than the code.

Pattern 6.5 Recursive Refinement

Establish a traceable relationship, based on refinement, between the most abstract spec and the detailed implementation (program code).

Intent

The abstract spec should bear a systematic relationship to the code, and this relationship should be expressed as a series of refinements. Many of these are decompositions, which break the problem into smaller pieces.

We wish to document the outcome of design.

Strategy

• Model separate views. Rather than build a single monolithic model, recognize when there are useful different external views of your component. Model each such view separately so that the model relates seamlessly to that part of the problem domain.

• Compose views into one spec. When designing, it helps to have a single combined spec on which you base your design; then you refine, and map to, only that single specification. Hence, compose your views into a single spec that you relate to your design and implementation.

• Refine the spec using one of the standard refinements. Some refinements are one-to-one; others are decompositions. The latter split the spec into several separate ones, each of which can be dealt with as a separate goal.

• Document each decomposition with a refinement that states how the constituents work together to fulfill the abstract spec.

• Each decomposition divides the job into a set of constituents, each with a specification that can be fulfilled separately. The same principles can be applied recursively to its design. Thus, you can specify an entire application as a type and then decompose it into internal collaborating components. If the components are of a nontrivial size, recursively model and specify each of them as a type.

• "Basic design" shortcuts some of the recursive refinement process by going straight for a set of decisions that accept the specification types as protoclasses. A judicious combination of basic design, subsequent optimization, and recursive refinement is practical for many projects.

• Use frameworks to build specifications and designs as well as refinements between the two. Frameworks (see Chapter 9, Model Frameworks and Template Packages) capture recurring patterns of types, collaborations, and refinements. Used properly and with the right tool support, frameworks let you document the main refinement decisions in a single place rather than duplicate them each place they are used. A single framework named Cache could have the design and refinement rationale independently of the many different contexts in which it is used.

Result

The result is a design that is traceable through the refinements.