a lot more than just plugging everything together and standing back. Bugs are typically found during system integration, and good planning can help us find the bugs quickly. By building up the system in phases and running properly chosen tests, we can often find bugs more easily. If we debug only a few modules at a time, we are more likely to uncover the simple bugs and able to easily recognize them. Only by fixing the simple bugs early will we be able to uncover the more complex or obscure bugs that can be identified only by giving the system a hard workout. We need to ensure during the architectural and component design phases that we make it as easy as possible to assemble the system in phases and test functions relatively independently.

System integration is difficult because it usually uncovers problems. It is often hard to observe the system in sufficient detail to determine exactly what is wrong—the debugging facilities for embedded systems are usually much more limited than what you would find on desktop systems. As a result, determining why things do not stet work correctly and how they can be fixed is a challenge in itself. Careful attention to inserting appropriate debugging facilities during design can help ease system integration problems, but the nature of embedded computing means that this phase will always be a challenge.

1.3 FORMALISMS FOR SYSTEM DESIGN

As mentioned in the last section, we perform a number of different design tasks at different levels of abstraction throughout this book: creating requirements and specifications, architecting the system, designing code, and designing tests. It is often helpful to conceptualize these tasks in diagrams. Luckily, there is a visual language that can be used to capture all these design tasks: the ***Unified Modeling Language (UML)*** [Boo99, Pil05]. UML was designed to be useful at many levels of abstraction in the design process. UML is useful because it encourages design by successive refinement and progressively adding detail to the design, rather than rethinking the design at each new level of abstraction.

UML is an ***object-oriented*** modeling language. We will see precisely what we mean by an object in just a moment, but object-oriented design emphasizes two concepts of importance:

- It encourages the design to be described as a number of interacting objects, rather than a few large monolithic blocks of code.
- At least some of those objects will correspond to real pieces of software or hardware in the system. We can also use UML to model the outside world that interacts with our system, in which case the objects may correspond to people or other machines. It is sometimes important to implement something we think of at a high level as a single object using several distinct pieces of code or to otherwise break up the object correspondence in the implementation.

However, thinking of the design in terms of actual objects helps us understand the natural structure of the system.

Object-oriented (often abbreviated OO) specification can be seen in two complementary ways:

- Object-oriented specification allows a system to be described in a way that closely models real-world objects and their interactions.
- Object-oriented specification provides a basic set of primitives that can be used to describe systems with particular attributes, irrespective of the relationships of those systems' components to real-world objects.

Both views are useful. At a minimum, object-oriented specification is a set of linguistic mechanisms. In many cases, it is useful to describe a system in terms of real-world analogs. However, performance, cost, and so on may dictate that we change the specification to be different in some ways from the real-world elements we are trying to model and implement. In this case, the object-oriented specification mechanisms are still useful.

What is the relationship between an object-oriented specification and an object-oriented programming language (such as C++ [Str97])? A specification language may not be executable. But both object-oriented specification and programming languages provide similar basic methods for structuring large systems.

Unified Modeling Language (UML)—the acronym is the name is a large language, and covering all of it is beyond the scope of this book. In this section, we introduce only a few basic concepts. In later chapters, as we need a few more UML concepts, we introduce them to the basic modeling elements introduced here. Because UML is so rich, there are many graphical elements in a UML diagram. It is important to be careful to use the correct drawing to describe something—for instance, UML distinguishes between arrows with open and filled-in arrowheads, and solid and broken lines. As you become more familiar with the language, uses of the graphical primitives will become more natural to you.

We also won't take a strict object-oriented approach. We may not always use objects for certain elements of a design—in some cases, such as when taking particular aspects of the implementation into account, it may make sense to use another design style. However, object-oriented design is widely applicable, and no designer can consider himself or herself design literate without understanding it.

1.3.1 Structural Description

By ***structural description***, we mean the basic components of the system; we will learn how to describe how these components act in the next section. The principal component of an object-oriented design is, naturally enough, the ***object***. An object includes a set of ***attributes*** that define its internal state. When implemented in a programming language, these attributes usually become variables or constants held in a data structure. In some cases, we will add the type of the attribute after

the attribute name for clarity, but we do not always have to specify a type for an attribute. An object describing a display (such as a CRT screen) is shown in UML notation in Figure 1.5. The text in the folded-corner page icon is a ***note***; it does not correspond to an object in the system and only serves as a comment. The attribute is, in this case, an array of pixels that holds the contents of the display. The object is identified in two ways: It has a unique name, and it is a member of a ***class***. The name is underlined to show that this is a description of an object and not of a class.

A class is a form of type definition—all objects derived from the same class have the same characteristics, although their attributes may have different values. A class defines the attributes that an object may have. It also defines the ***operations*** that determine how the object interacts with the rest of the world. In a programming language, the operations would become pieces of code used to manipulate the object. The UML description of the *Display* class is shown in Figure 1.6. The class has the name that we saw used in the *d*1 object since *d*1 is an instance of class *Display*. The *Display* class defines the *pixels* attribute seen in the object; remember that when we instantiate the class an object, that object will have its own memory so that different objects of the same class have their own values for the attributes. Other classes can examine and modify class attributes; if we have to do something more complex than use the attribute directly, we define a behavior to perform that function.

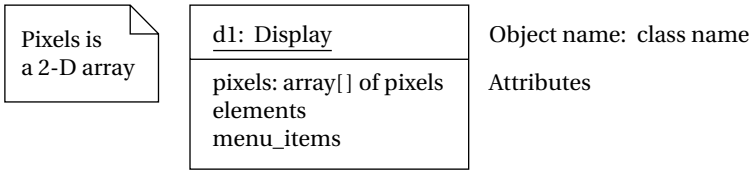


FIGURE 1.5

An object in UML notation.

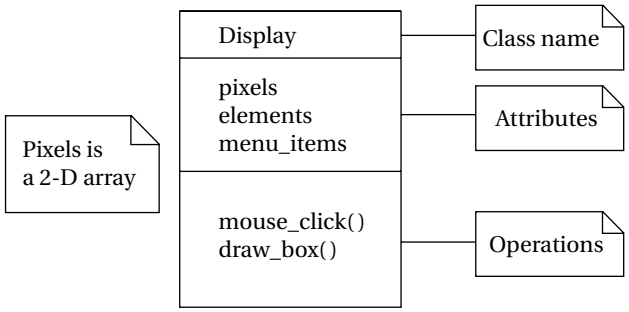


FIGURE 1.6

A class in UML notation.

A class defines both the ***interface*** for a particular type of object and that object's ***implementation***. When we use an object, we do not directly manipulate its attributes—we can only read or modify the object's state through the operations that define the interface to the object. (The implementation includes both the attributes and whatever code is used to implement the operations.) As long as we do not change the behavior of the object seen at the interface, we can change the implementation as much as we want. This lets us improve the system by, for example, speeding up an operation or reducing the amount of memory required without requiring changes to anything else that uses the object.

Clearly, the choice of an interface is a very important decision in object-oriented design. The proper interface must provide ways to access the object's state (since we cannot directly see the attributes) as well as ways to update the state. We need to make the object's interface general enough so that we can make full use of its capabilities. However, excessive generality often makes the object large and slow. Big, complex interfaces also make the class definition difficult for designers to understand and use properly.

There are several types of ***relationships*** that can exist between objects and classes:

- ***Association*** occurs between objects that communicate with each other but have no ownership relationship between them.
- ***Aggregation*** describes a complex object made of smaller objects.
- ***Composition*** is a type of aggregation in which the owner does not allow access to the component objects.
- ***Generalization*** allows us to define one class in terms of another.

The elements of a UML class or object do not necessarily directly correspond to statements in a programming language—if the UML is intended to describe something more abstract than a program, there may be a significant gap between the contents of the UML and a program implementing it. The attributes of an object do not necessarily reflect variables in the object. An attribute is some value that reflects the current state of the object. In the program implementation, that value could be computed from some other internal variables. The behaviors of the object would, in a higher-level specification, reflect the basic things that can be done with an object. Implementing all these features may require breaking up a behavior into several smaller behaviors—for example, initialize the object before you start to change its internal state-derived classes.

Unified Modeling Language, like most object-oriented languages, allows us to define one class in terms of another. An example is shown in Figure 1.7, where we ***derive*** two particular types of displays. The first, *BW_display*, describes a black-and-white display. This does not require us to add new attributes or operations, but we can specialize both to work on one-bit pixels. The second, *Color_map_display*, uses a graphic device known as a color map to allow the user to select from a

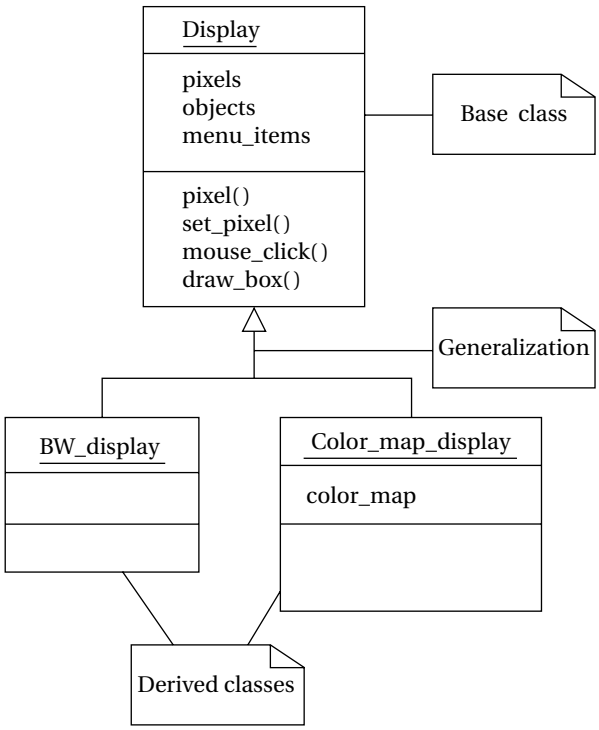


FIGURE 1.7

Derived classes as a form of generalization in UML.

large number of available colors even with a small number of bits per pixel. This class defines a *color_map* attribute that determines how pixel values are mapped onto display colors. A ***derived class*** inherits all the attributes and operations from its ***base class***. In this class, *Display* is the base class for the two derived classes. A derived class is defined to include all the attributes of its base class. This relation is transitive—if *Display* were derived from another class, both *BW_display* and *Color_map_display* would inherit all the attributes and operations of *Display's* base class as well. Inheritance has two purposes. It of course allows us to succinctly describe one class that shares some characteristics with another class. Even more important, it captures those relationships between classes and documents them. If we ever need to change any of the classes, knowledge of the class structure helps us determine the reach of changes—for example, should the change affect only *Color_map_display* objects or should it change all Display objects?

Unified Modeling Language considers inheritance to be one form of generalization. A generalization relationship is shown in a UML diagram as an arrow with an open (unfilled) arrowhead. Both *BW_display* and *Color_map_display* are specific

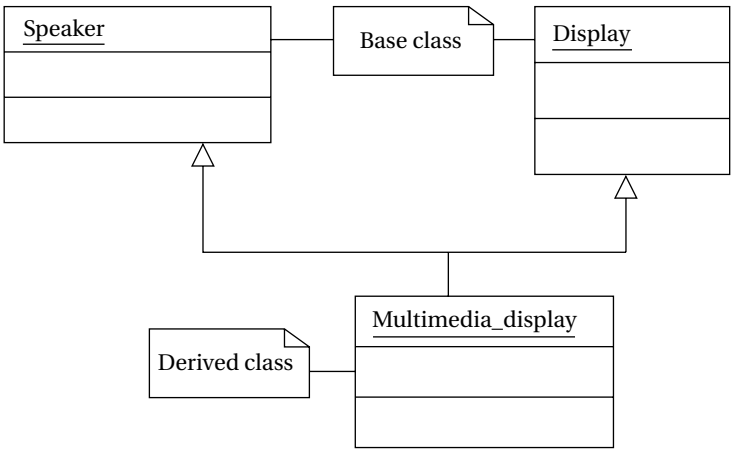


FIGURE 1.8
Multiple inheritance in UML.

versions of *Display*, so *Display* generalizes both of them. UML also allows us to define ***multiple inheritance***, in which a class is derived from more than one base class. (Most object-oriented programming languages support multiple inheritance as well.) An example of multiple inheritance is shown in Figure 1.8; we have omitted the details of the classes' attributes and operations for simplicity. In this case, we have created a *Multimedia_display* class by combining the *Display* class with a *Speaker* class for sound. The derived class inherits all the attributes and operations of both its base classes, *Display* and *Speaker*. Because multiple inheritance causes the sizes of the attribute set and operations to expand so quickly, it should be used with care.

A ***link*** describes a relationship between objects; association is to link as class is to object. We need links because objects often do not stand alone; associations let us capture type information about these links. Figure 1.9 shows examples of links and an association. When we consider the actual objects in the system, there is a set of messages that keeps track of the current number of active messages (two in this example) and points to the active messages. In this case, the link defines the *contains* relation. When generalized into classes, we define an association between the message set class and the message class. The association is drawn as a line between the two labeled with the name of the association, namely, *contains*. The ball and the number at the message class end indicate that the message set may include zero or more message objects. Sometimes we may want to attach data to the links themselves; we can specify this in the association by attaching a class-like box to the association's edge, which holds the association's data.

Typically, we find that we use a certain combination of elements in an object or class many times. We can give these patterns names, which are called ***stereotypes***

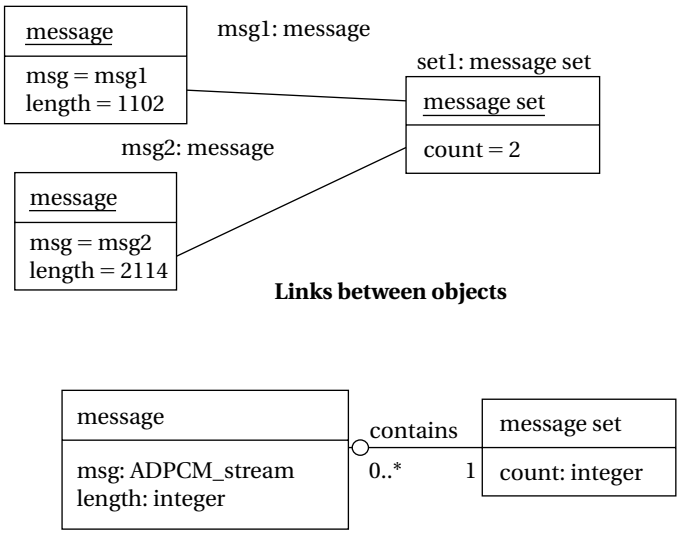


FIGURE 1.9

Links and association.

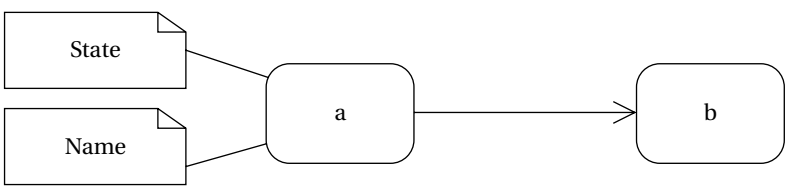


FIGURE 1.10

A state and transition in UML.

in UML. A stereotype name is written in the form <<signal>>. Figure 1.11 shows a stereotype for a signal, which is a communication mechanism.

1.3.2 Behavioral Description

We have to specify the behavior of the system as well as its structure. One way to specify the behavior of an operation is a ***state machine***. Figure 1.10 shows UML states; the transition between two states is shown by a skeleton arrow.

These state machines will not rely on the operation of a clock, as in hardware; rather, changes from one state to another are triggered by the occurrence of ***events***.

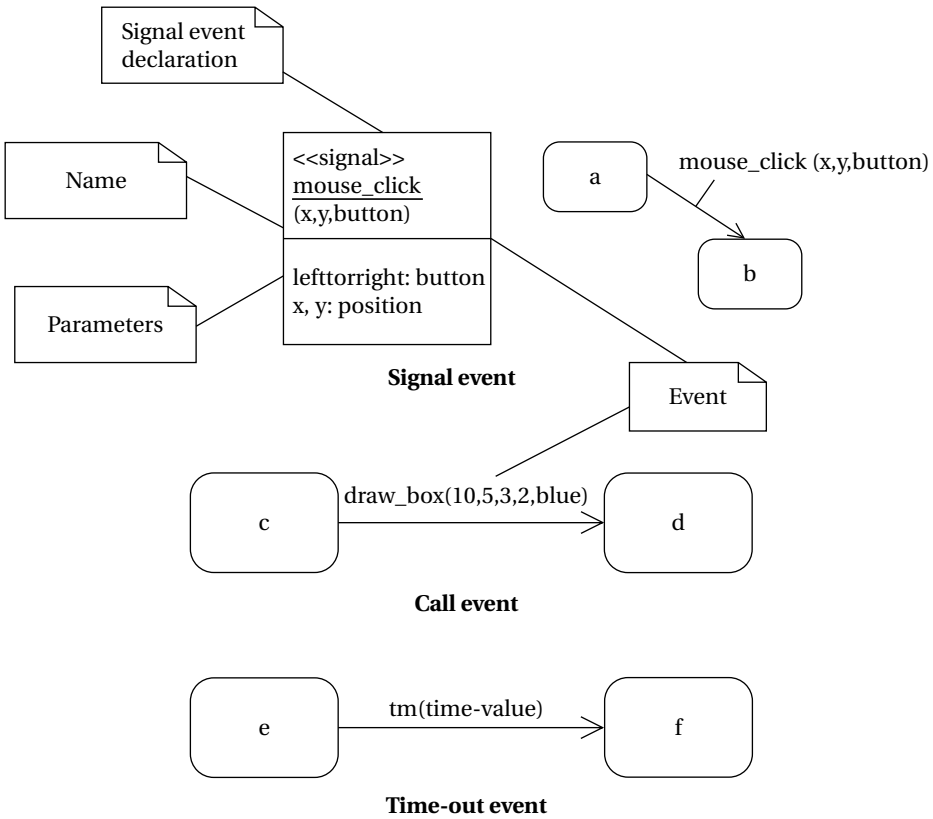


FIGURE 1.11

Signal, call, and time-out events in UML.

An event is some type of action. The event may originate outside the system, such as a user pressing a button. It may also originate inside, such as when one routine finishes its computation and passes the result on to another routine. We will concentrate on the following three types of events defined by UML, as illustrated in Figure 1.11:

- A ***signal*** is an asynchronous occurrence. It is defined in UML by an object that is labeled as a *<<signal>>*. The object in the diagram serves as a declaration of the event's existence. Because it is an object, a signal may have parameters that are passed to the signal's receiver.
- A ***call event*** follows the model of a procedure call in a programming language.
- A ***time-out event*** causes the machine to leave a state after a certain amount of time. The label *tm(time-value)* on the edge gives the amount of time after which the transition occurs. A time-out is generally implemented with an

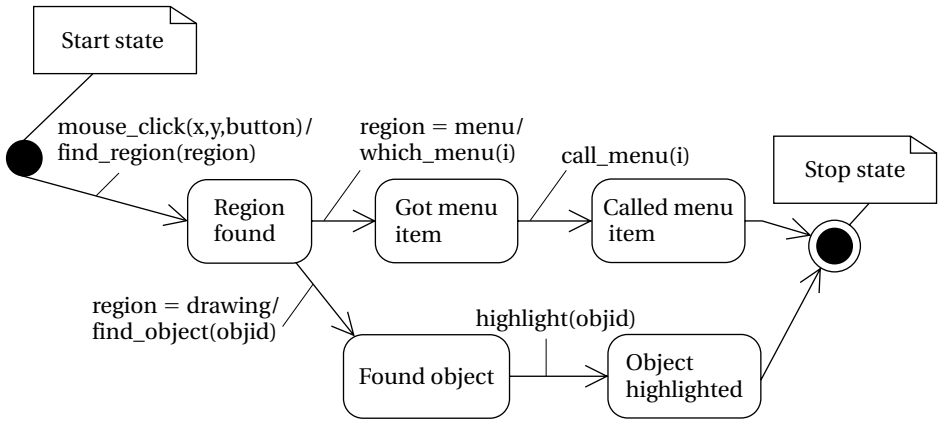


FIGURE 1.12

A state machine specification in UML.

external timer. This notation simplifies the specification and allows us to defer implementation details about the time-out mechanism.

We show the occurrence of all types of signals in a UML diagram in the same way—as a label on a transition.

Let's consider a simple state machine specification to understand the semantics of UML state machines. A state machine for an operation of the display is shown in Figure 1.12. The start and stop states are special states that help us to organize the flow of the state machine. The states in the state machine represent different conceptual operations. In some cases, we take conditional transitions out of states based on inputs or the results of some computation done in the state. In other cases, we make an unconditional transition to the next state. Both the unconditional and conditional transitions make use of the call event. Splitting a complex operation into several states helps document the required steps, much as subroutines can be used to structure code.

It is sometimes useful to show the sequence of operations over time, particularly when several objects are involved. In this case, we can create a sequence diagram, like the one for a mouse click scenario shown in Figure 1.13. A ***sequence diagram*** is somewhat similar to a hardware timing diagram, although the time flows vertically in a sequence diagram, whereas time typically flows horizontally in a timing diagram. The sequence diagram is designed to show a particular scenario or choice of events—it is not convenient for showing a number of mutually exclusive possibilities. In this case, the sequence shows what happens when a mouse click is on the menu region. Processing includes three objects shown at the top of the diagram. Extending below each object is its *lifeline*, a dashed line that shows how long the object is alive. In this case, all the objects remain alive for the entire sequence, but in other cases objects may be created or destroyed during processing. The boxes

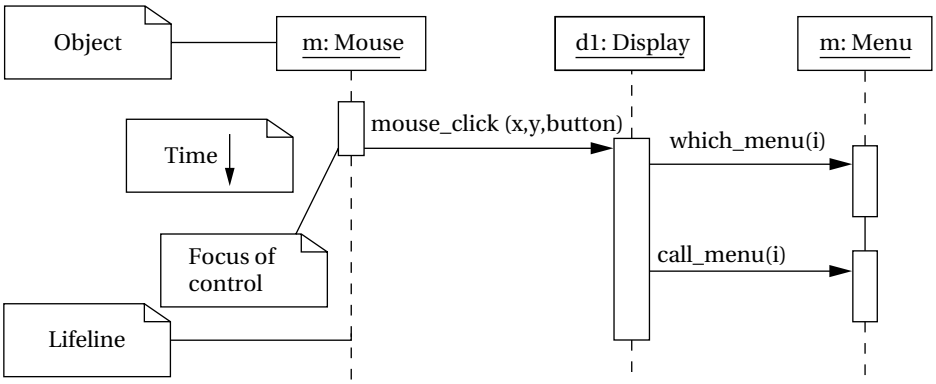


FIGURE 1.13

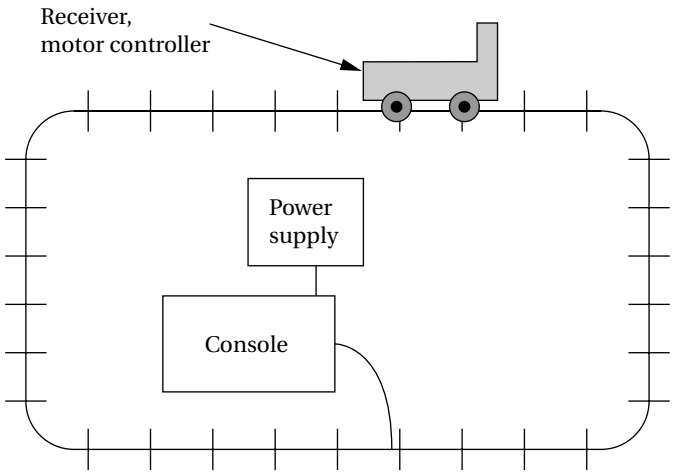
A sequence diagram in UML.

along the lifelines show the *focus of control* in the sequence, that is, when the object is actively processing. In this case, the mouse object is active only long enough to create the *mouse_click* event. The display object remains in play longer; it in turn uses call events to invoke the menu object twice: once to determine which menu item was selected and again to actually execute the menu call. The find_region( ) call is internal to the display object, so it does not appear as an event in the diagram.

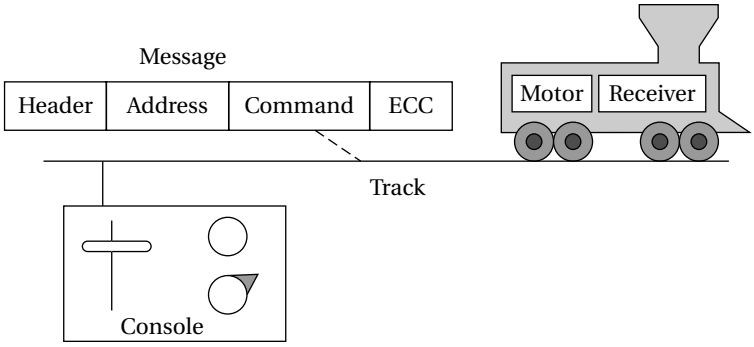
1.4 MODEL TRAIN CONTROLLER

In order to learn how to use UML to model systems, we will specify a simple system, a model train controller, which is illustrated in Figure 1.14. The user sends messages to the train with a control box attached to the tracks. The control box may have familiar controls such as a throttle, emergency stop button, and so on. Since the train receives its electrical power from the two rails of the track, the control box can send signals to the train over the tracks by modulating the power supply voltage. As shown in the figure, the control panel sends packets over the tracks to the receiver on the train. The train includes analog electronics to sense the bits being transmitted and a control system to set the train motor's speed and direction based on those commands. Each packet includes an address so that the console can control several trains on the same track; the packet also includes an error correction code (ECC) to guard against transmission errors. This is a one-way communication system—the model train cannot send commands back to the user.

We start by analyzing the requirements for the train control system. We will base our system on a real standard developed for model trains. We then develop two specifications: a simple, high-level specification and then a more detailed specification.



System setup



Signaling the train

FIGURE 1.14

A model train control system.

1.4.1 Requirements

Before we can create a system specification, we have to understand the requirements. Here is a basic set of requirements for the system:

- The console shall be able to control up to eight trains on a single track.
- The speed of each train shall be controllable by a throttle to at least 63 different levels in each direction (forward and reverse).

- There shall be an inertia control that shall allow the user to adjust the responsiveness of the train to commanded changes in speed. Higher inertia means that the train responds more slowly to a change in the throttle, simulating the inertia of a large train. The inertia control will provide at least eight different levels.
- There shall be an emergency stop button.
- An error detection scheme will be used to transmit messages.

We can put the requirements into our chart format:

Name	Model train controller
Purpose	Control speed of up to eight model trains
Inputs	Throttle, inertia setting, emergency stop, train number
Outputs	Train control signals
Functions	Set engine speed based upon inertia settings; respond to emergency stop
Performance	Can update train speed at least 10 times per second
Manufacturing cost	$50
Power	10W (plugs into wall)
Physical size and weight	Console should be comfortable for two hands, approximate size of standard keyboard; weight <2 pounds

We will develop our system using a widely used standard for model train control. We could develop our own train control system from scratch, but basing our system upon a standard has several advantages in this case: It reduces the amount of work we have to do and it allows us to use a wide variety of existing trains and other pieces of equipment.

1.4.2 DCC

The **Digital Command Control (DCC)** standard (http://www.nmra.org/standards/DCC/standards_rps/DCCStds.html) was created by the National Model Railroad Association to support interoperable digitally-controlled model trains. Hobbyists started building homebrew digital control systems in the 1970s and Marklin developed its own digital control system in the 1980s. DCC was created to provide a standard that could be built by any manufacturer so that hobbyists could mix and match components from multiple vendors.

The DCC standard is given in two documents:

- Standard S-9.1, the DCC Electrical Standard, defines how bits are encoded on the rails for transmission.
- Standard S-9.2, the DCC Communication Standard, defines the packets that carry information.

Any DCC-conforming device must meet these specifications. DCC also provides several recommended practices. These are not strictly required but they provide some hints to manufacturers and users as to how to best use DCC.

The DCC standard does not specify many aspects of a DCC train system. It doesn't define the control panel, the type of microprocessor used, the programming language to be used, or many other aspects of a real model train system. The standard concentrates on those aspects of system design that are necessary for interoperability. Overstandardization, or specifying elements that do not really need to be standardized, only makes the standard less attractive and harder to implement.

The Electrical Standard deals with voltages and currents on the track. While the electrical engineering aspects of this part of the specification are beyond the scope of the book, we will briefly discuss the data encoding here. The standard must be carefully designed because the main function of the track is to carry power to the locomotives. The signal encoding system should not interfere with power transmission either to DCC or non-DCC locomotives. A key requirement is that the data signal should not change the DC value of the rails.

The data signal swings between two voltages around the power supply voltage. As shown in Figure 1.15, bits are encoded in the time between transitions, not by voltage levels. A 0 is at least 100 μs while a 1 is nominally 58 μs. The durations of the high (above nominal voltage) and low (below nominal voltage) parts of a bit are equal to keep the DC value constant. The specification also gives the allowable variations in bit times that a conforming DCC receiver must be able to tolerate.

The standard also describes other electrical properties of the system, such as allowable transition times for signals.

The DCC Communication Standard describes how bits are combined into packets and the meaning of some important packets. Some packet types are left undefined in the standard but typical uses are given in Recommended Practices documents.

We can write the basic packet format as a regular expression:

$$\text{PSA(sD)} + \text{E} \tag{1.1}$$

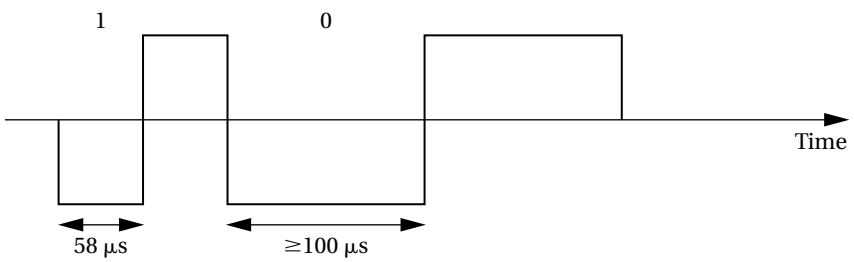


FIGURE 1.15

Bit encoding in DCC.

In this regular expression:

- *P* is the preamble, which is a sequence of at least 10 1 bits. The command station should send at least 14 of these 1 bits, some of which may be corrupted during transmission.
- *S* is the packet start bit. It is a 0 bit.
- *A* is an address data byte that gives the address of the unit, with the most significant bit of the address transmitted first. An address is eight bits long. The addresses 00000000, 11111110, and 11111111 are reserved.
- *s* is the data byte start bit, which, like the packet start bit, is a 0.
- *D* is the data byte, which includes eight bits. A data byte may contain an address, instruction, data, or error correction information.
- *E* is a packet end bit, which is a 1 bit.

A packet includes one or more data byte start bit/data byte combinations. Note that the address data byte is a specific type of data byte.

A ***baseline packet*** is the minimum packet that must be accepted by all DCC implementations. More complex packets are given in a Recommended Practice document. A baseline packet has three data bytes: an address data byte that gives the intended receiver of the packet; the instruction data byte provides a basic instruction; and an error correction data byte is used to detect and correct transmission errors.

The instruction data byte carries several pieces of information. Bits 0–3 provide a 4-bit speed value. Bit 4 has an additional speed bit, which is interpreted as the least significant speed bit. Bit 5 gives direction, with 1 for forward and 0 for reverse. Bits 7–8 are set at 01 to indicate that this instruction provides speed and direction.

The error correction databyte is the bitwise exclusive OR of the address and instruction data bytes.

The standard says that the command unit should send packets frequently since a packet may be corrupted. Packets should be separated by at least 5 ms.

1.4.3 Conceptual Specification

Digital Command Control specifies some important aspects of the system, particularly those that allow equipment to interoperate. But DCC deliberately does not specify everything about a model train control system. We need to round out our specification with details that complement the DCC spec. A ***conceptual specification*** allows us to understand the system a little better. We will use the experience gained by writing the conceptual specification to help us write a detailed specification to be given to a system architect. This specification does not correspond to what any commercial DCC controllers do, but it is simple enough to allow us to cover some basic concepts in system design.

A train control system turns ***commands*** into ***packets***. A command comes from the command unit while a packet is transmitted over the rails. Commands and packets may not be generated in a 1-to-1 ratio. In fact, the DCC standard says that command units should resend packets in case a packet is dropped during transmission.

We now need to model the train control system itself. There are clearly two major subsystems: the command unit and the train-board component as shown in Figure 1.16. Each of these subsystems has its own internal structure. The basic relationship between them is illustrated in Figure 1.17. This figure shows a UML ***collaboration diagram***; we could have used another type of figure, such as a class or object diagram, but we wanted to emphasize the transmit/receive relationship between these major subsystems. The command unit and receiver are each represented by objects; the command unit sends a sequence of packets to the train's receiver, as illustrated by the arrow. The notation on the arrow provides both the type of message sent and its sequence in a flow of messages; since the console sends all the messages, we have numbered the arrow's messages as 1..*n*. Those messages are of course carried over the track. Since the track is not a computer component and is purely passive, it does not appear in the diagram. However, it would be perfectly legitimate to model the track in the collaboration diagram, and in some situations it may be wise to model such nontraditional components in the specification diagrams. For example, if we are worried about what happens when the track breaks,

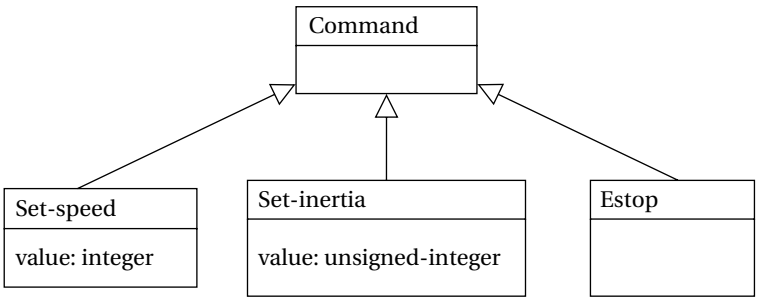


FIGURE 1.16

Class diagram for the train controller messages.

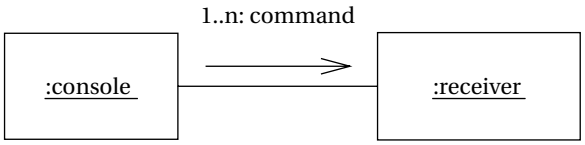


FIGURE 1.17

UML collaboration diagram for major subsystems of the train controller system.

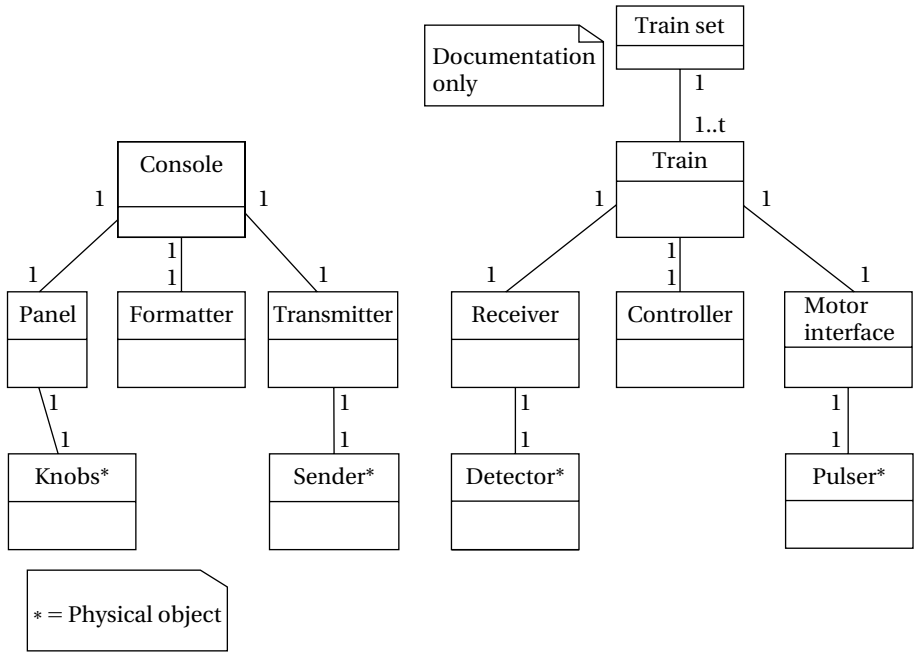


FIGURE 1.18

A UML class diagram for the train controller showing the composition of the subsystems.

modeling the tracks would help us identify failure modes and possible recovery mechanisms.

Let's break down the command unit and receiver into their major components. The console needs to perform three functions: read the state of the front panel on the command unit, format messages, and transmit messages. The train receiver must also perform three major functions: receive the message, interpret the message (taking into account the current speed, inertia setting, etc.), and actually control the motor. In this case, let's use a class diagram to represent the design; we could also use an object diagram if we wished. The UML class diagram is shown in Figure 1.18. It shows the console class using three classes, one for each of its major components. These classes must define some behaviors, but for the moment we will concentrate on the basic characteristics of these classes:

- The *Console* class describes the command unit's front panel, which contains the analog knobs and hardware to interface to the digital parts of the system.
- The *Formatter* class includes behaviors that know how to read the panel knobs and creates a bit stream for the required message.
- The *Transmitter* class interfaces to analog electronics to send the message along the track.

There will be one instance of the *Console* class and one instance of each of the component classes, as shown by the numeric values at each end of the relationship links. We have also shown some special classes that represent analog components, ending the name of each with an asterisk:

- *Knobs** describes the actual analog knobs, buttons, and levers on the control panel.
- *Sender** describes the analog electronics that send bits along the track.

Likewise, the Train makes use of three other classes that define its components:

- The *Receiver* class knows how to turn the analog signals on the track into digital form.
- The *Controller* class includes behaviors that interpret the commands and figures out how to control the motor.
- The *Motor interface* class defines how to generate the analog signals required to control the motor.

We define two classes to represent analog components:

- *Detector** detects analog signals on the track and converts them into digital form.
- *Pulser** turns digital commands into the analog signals required to control the motor speed.

We have also defined a special class, *Train set*, to help us remember that the system can handle multiple trains. The values on the relationship edge show that one train set can have *t* trains. We would not actually implement the train set class, but it does serve as useful documentation of the existence of multiple receivers.

1.4.4 Detailed Specification

Now that we have a conceptual specification that defines the basic classes, let's refine it to create a more detailed specification. We won't make a complete specification, but we will add detail to the classes and look at some of the major decisions in the specification process to get a better handle on how to write good specifications.

At this point, we need to define the analog components in a little more detail because their characteristics will strongly influence the *Formatter* and *Controller*. Figure 1.19 shows a class diagram for these classes; this diagram shows a little more detail than Figure 1.18 since it includes attributes and behaviors of these classes. The *Panel* has three knobs: *train* number (which train is currently being controlled), *speed* (which can be positive or negative), and *inertia*. It also has one button for *emergency-stop*. When we change the train number setting, we also want to reset the other controls to the proper values for that train so that the previous train's control settings are not used to change the current train's settings. To do this, *Knobs** must

provide a *set-knobs* behavior that allows the rest of the system to modify the knob settings. (If we wanted or needed to model the user, we would expand on this class definition to provide methods that a user object would call to specify these parameters.) The motor system takes its motor commands in two parts. The *Sender* and *Detector* classes are relatively simple: They simply put out and pick up a bit, respectively.

To understand the *Pulser* class, let's consider how we actually control the train motor's speed. As shown in Figure 1.20, the speed of electric motors is commonly controlled using pulse-width modulation: Power is applied in a pulse for a fraction of some fixed interval, with the fraction of the time that power is applied determining the speed. The digital interface to the motor system specifies that pulse width as an integer, with the maximum value being maximum engine speed. A separate binary value controls direction. Note that the motor control takes an unsigned speed with a

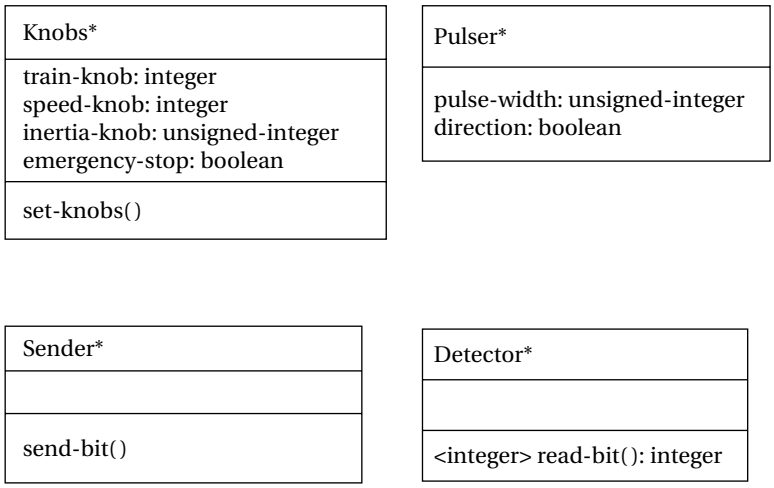


FIGURE 1.19

Classes describing analog physical objects in the train control system.

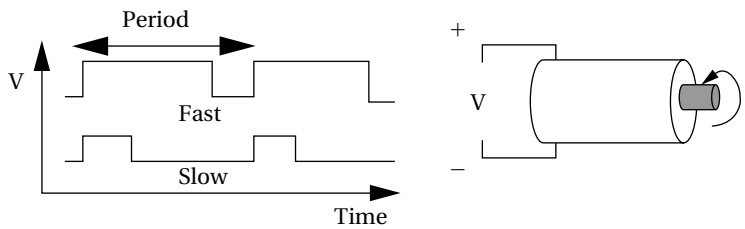


FIGURE 1.20

Controlling motor speed by pulse-width modulation.

separate direction, while the panel specifies speed as a signed integer, with negative speeds corresponding to reverse.

Figure 1.21 shows the classes for the panel and motor interfaces. These classes form the software interfaces to their respective physical devices. The *Panel* class defines a behavior for each of the controls on the panel; we have chosen not to define an internal variable for each control since their values can be read directly from the physical device, but a given implementation may choose to use internal variables. The *new-settings* behavior uses the *set-knobs* behavior of the *Knobs** class to change the knobs settings whenever the train number setting is changed. The *Motor-interface* defines an attribute for speed that can be set by other classes. As we will see in a moment, the controller's job is to incrementally adjust the motor's speed to provide smooth acceleration and deceleration.

The *Transmitter* and *Receiver* classes are shown in Figure 1.22. They provide the software interface to the physical devices that send and receive bits along the track.

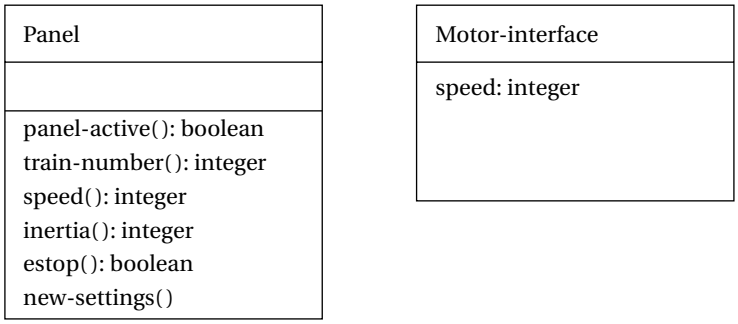


FIGURE 1.21

Class diagram for the Panel and Motor interface.

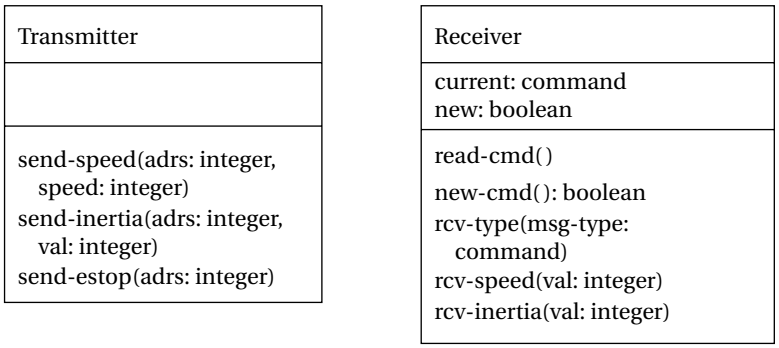


FIGURE 1.22

Class diagram for the Transmitter and Receiver.

The *Transmitter* provides a distinct behavior for each type of message that can be sent; it internally takes care of formatting the message. The *Receiver* class provides a *read-cmd* behavior to read a message off the tracks. We can assume for now that the receiver object allows this behavior to run continuously to monitor the tracks and intercept the next command. (We consider how to model such continuously running behavior as processes in Chapter 6.) We use an internal variable to hold the current command. Another variable holds a flag showing when the command has been processed. Separate behaviors let us read out the parameters for each type of command; these messages also reset the new flag to show that the command has been processed. We do not need a separate behavior for an *Estop* message since it has no parameters—knowing the type of message is sufficient.

Now that we have specified the subsystems around the formatter and controller, it is easier to see what sorts of interfaces these two subsystems may need.

The *Formatter* class is shown in Figure 1.23. The formatter holds the current control settings for all of the trains. The *send-command* method is a utility function that serves as the interface to the transmitter. The *operate* function performs the basic actions for the object. At this point, we only need a simple specification, which states that the formatter repeatedly reads the panel, determines whether any settings have changed, and sends out the appropriate messages. The *panel-active* behavior returns true whenever the panel's values do not correspond to the current values.

The role of the formatter during the panel's operation is illustrated by the sequence diagram of Figure 1.24. The figure shows two changes to the knob settings: first to the throttle, inertia, or emergency stop; then to the train number. The panel is called periodically by the formatter to determine if any control settings have changed. If a setting has changed for the current train, the formatter decides to send a command, issuing a *send-command* behavior to cause the transmitter to send the bits. Because transmission is serial, it takes a noticeable amount of time for the transmitter to finish a command; in the meantime, the formatter continues to

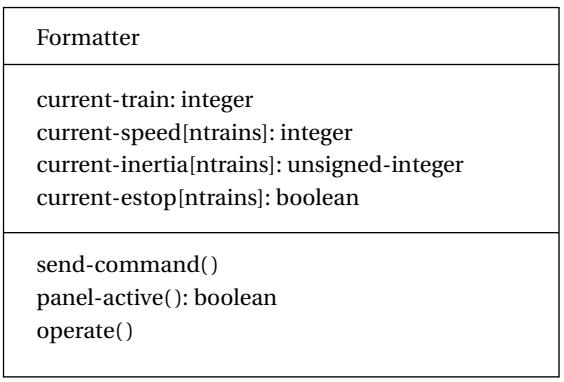


FIGURE 1.23

Class diagram for the Formatter class.

check the panel's control settings. If the train number has changed, the formatter must cause the knob settings to be reset to the proper values for the new train.

We have not yet specified the operation of any of the behaviors. We define what a behavior does by writing a state diagram. The state diagram for a very simple version of the *operate* behavior of the *Formatter* class is shown in Figure 1.25. This behavior watches the panel for activity: If the train number changes, it updates

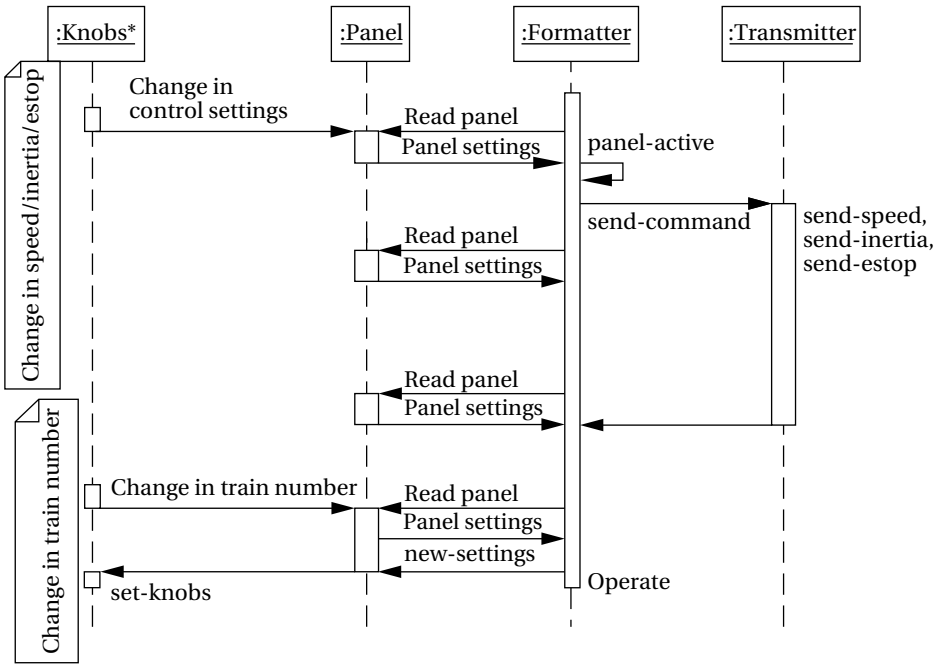


FIGURE 1.24

Sequences diagram for transmitting a control input.

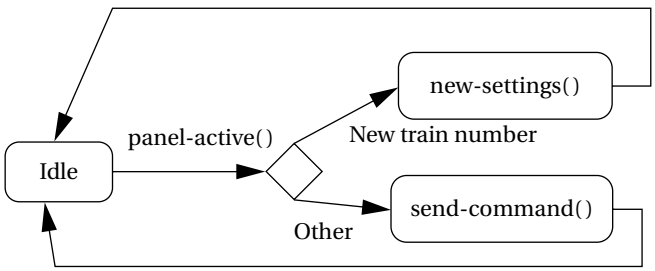


FIGURE 1.25

State diagram for the formatter operate behavior.

the panel display; otherwise, it causes the required message to be sent. Figure 1.26 shows a state diagram for the *panel-active* behavior.

The definition of the train's *Controller* class is shown in Figure 1.27. The *operate* behavior is called by the receiver when it gets a new command; *operate* looks at the contents of the message and uses the *issue-command* behavior to change the speed, direction, and inertia settings as necessary. A specification for *operate* is shown in Figure 1.28.

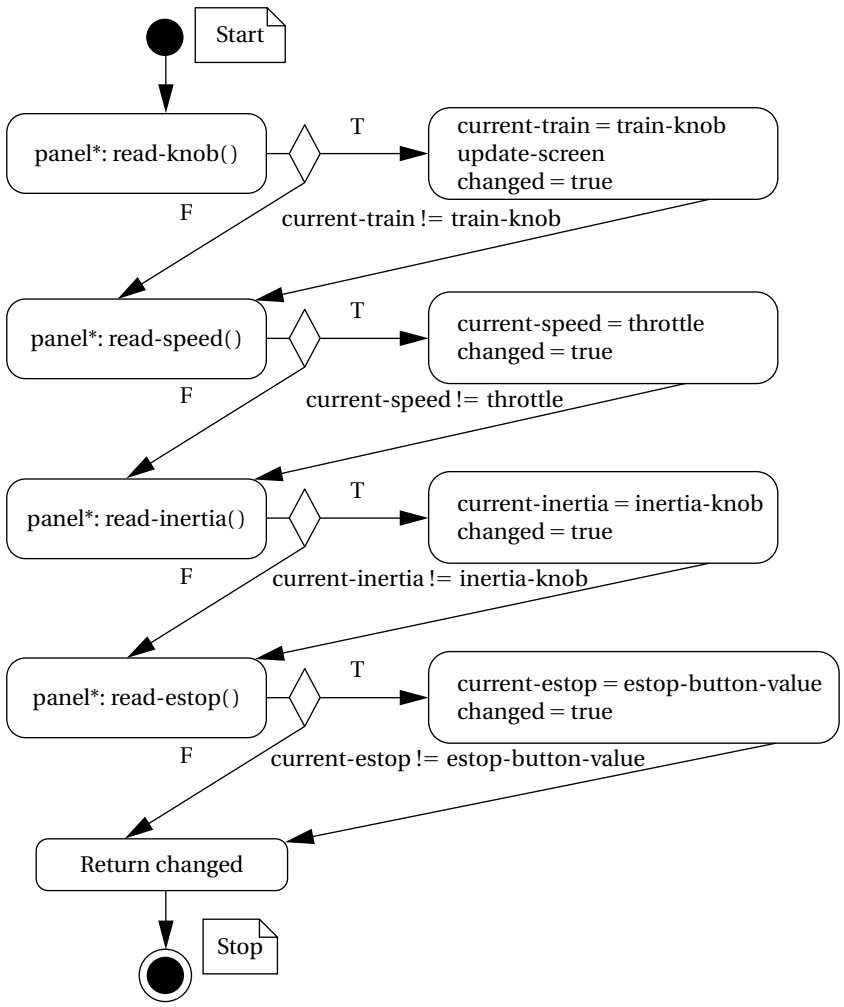


FIGURE 1.26

State diagram for the panel-active behavior.

The operation of the *Controller* class during the reception of a *set-speed* command is illustrated in Figure 1.29. The *Controller's operate* behavior must execute several behaviors to determine the nature of the message. Once the speed command has been parsed, it must send a sequence of commands to the motor to smoothly change the train's speed.

It is also a good idea to refine our notion of a command. These changes result from the need to build a potentially upward-compatible system. If the messages were entirely internal, we would have more freedom in specifying messages that we could use during architectural design. But since these messages must work with a variety of trains and we may want to add more commands in a later version of the system, we need to specify the basic features of messages for compatibility. There are three important issues. First, we need to specify the number of bits used to determine the message type. We choose three bits, since that gives us five unused message codes. Second, we need to include information about the length of the

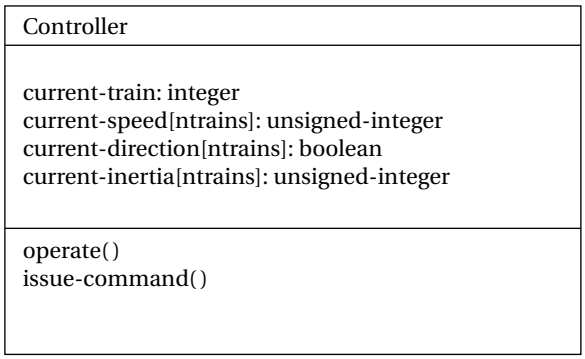


FIGURE 1.27

Class diagram for the Controller class.

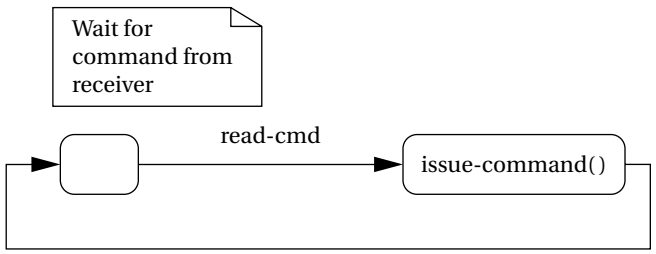


FIGURE 1.28

State diagram for the Controller operate behavior.

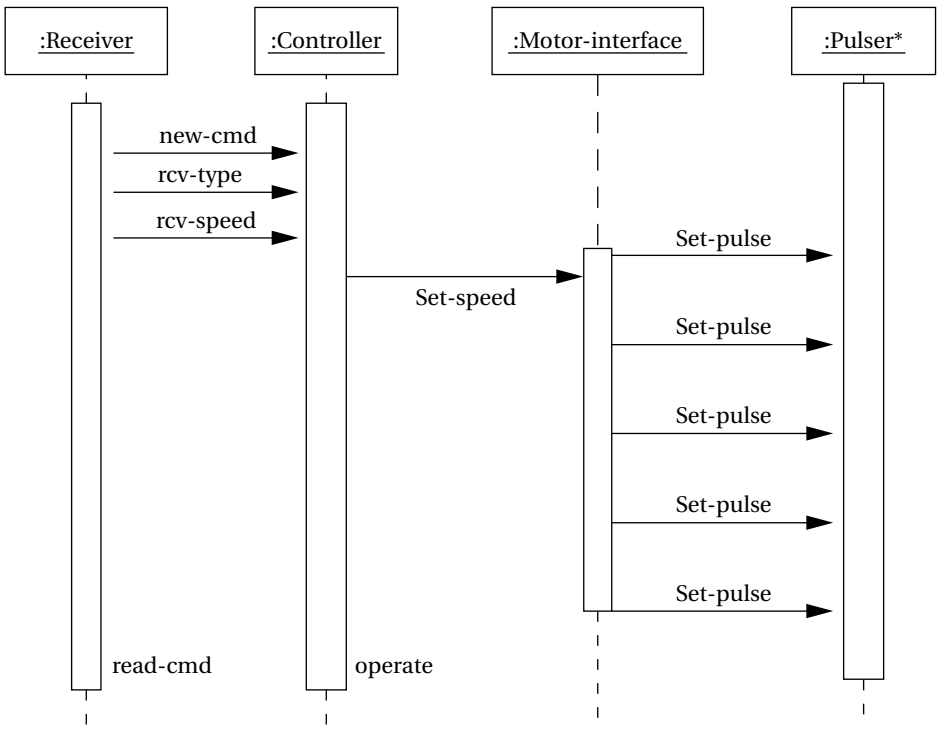


FIGURE 1.29

Sequence diagram for a set-speed command received by the train.

data fields, which is determined by the resolution for speeds and inertia set by the requirements. Third, we need to specify the error correction mechanism; we choose to use a single-parity bit. We can update the classes to provide this extra information as shown in Figure 1.30.

1.4.5 Lessons Learned

We have learned a couple of things in this exercise beyond gaining experience with UML notation. First, standards are important. We often can't avoid working with standards but standards often save us work and allow us to make use of components designed by others. Second, specifying a system is not easy. You often learn a lot about the system you are trying to build by writing a specification. Third, specification invariably requires making some choices that may influence the implementation. Good system designers use their experience and intuition to guide them when these kinds of choices must be made.

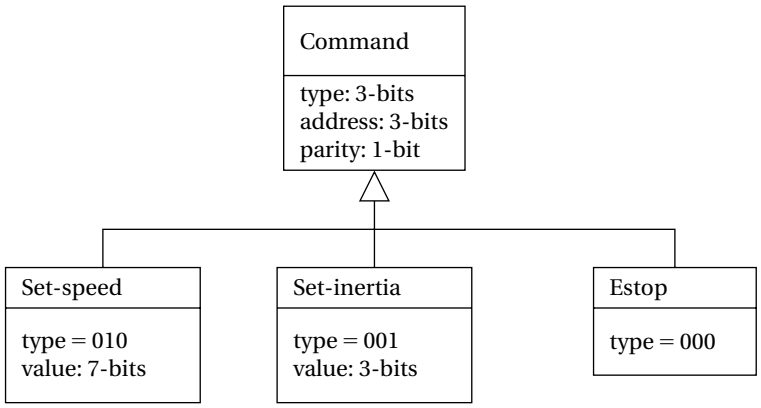


FIGURE 1.30

Refined class diagram for the train controller commands.

1.5 A GUIDED TOUR OF THIS BOOK

The most efficient way to learn all the necessary concepts is to move from the bottom–up. This book is arranged so that you learn about the properties of components and build toward more complex systems and a more complete view of the system design process. Veteran designers have learned enough bottom-up knowledge from experience to know how to use a top–down approach to designing a system, but when learning things for the first time, the bottom–up approach allows you to build more sophisticated concepts on the basis of lower-level ideas.

We will use several organizational devices throughout the book to help you. Application Examples focus on a particular end-use application and how it relates to embedded system design. We will also make use of Programming Examples to describe software designs. In addition to these examples, each chapter will use a significant system design example to demonstrate the major concepts of the chapter.

Each chapter includes questions that are intended to be answered on paper as homework assignments. The chapters also include lab exercises. These are more open ended and are intended to suggest activities that can be performed in the lab to help illuminate various concepts in the chapter.

Throughout the book, we will use two CPUs as examples: the ARM RISC processor and the Texas Instruments TI TMS320C55x™ (C55x) digital signal processor (DSP). Both are well-known microprocessors used in many embedded applications. Using real microprocessors helps make concepts more concrete. However, our aim is to learn concepts that can be applied to many different microprocessors, not only ARM and the C55x. While microprocessors will evolve over time (Warhol's Law of