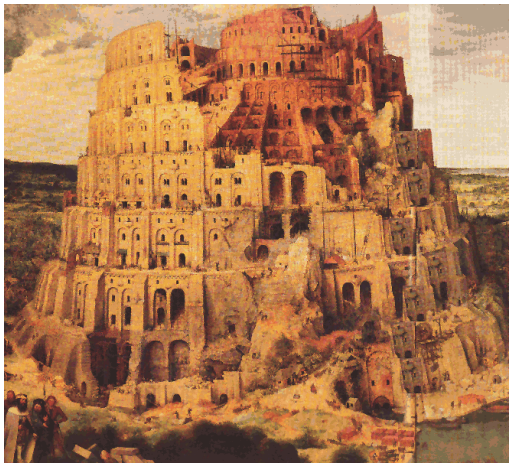

PTOLEMY II

HETEROGENEOUS CONCURRENT MODELING AND DESIGN IN JAVA

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VOLUME 3: PTOLEMY II DOMAINS

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VOLUME 3

PTOLEMY II DOMAINS

This volume describes Ptolemy II domains. The domains implement models of computation, which are summarized in chapter 1. Most of these models of computation can be viewed as a framework for component-based design, where the framework defines the interaction mechanism between the components. Some of the domains (CSP, DDE, and PN) are thread-oriented, meaning that the components implement Java threads. These can be viewed, therefore, as abstractions upon which to build threaded Java programs. These abstractions are much easier to use (much higher level) than the raw threads and monitors of Java. Others (CT, DE, SDF) of the domains implement their own scheduling between actors, rather than relying on threads. This usual results in much more efficient execution. The Giotto domain, which addresses real-time computation, is not threaded, but has concurrency features similar to threaded domains. The FSM domain is in a category by itself, since in it, the components are not producers and consumers of data, but rather are states. The non-threaded domains are described first, followed by FSM and Giotto, followed by the threaded domains. Within this grouping, the domains are ordered alphabetically (which is an arbitrary choice).

Volume 1 is an introduction to Ptolemy II, including tutorials on use of the software, and volume 2 describes the Ptolemy II software architecture.

Contents

Volume 3

1

DE Domain

Authors: *Lukito Muliadi*
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1.1 Introduction

The discrete-event (DE) domain supports time-oriented models of systems such as queueing systems, communication networks, and digital hardware. In this domain, actors communicate by sending *events*, where an event is a data value (a token) and a *time stamp*. A DE scheduler ensures that events are processed chronologically according to this time stamp by firing those actors whose available input events are the oldest (having the earliest time stamp of all pending events).

A key strength in our implementation is that simultaneous events (those with identical time stamps) are handled systematically and deterministically. Another second key strength is that the global event queue uses an efficient structure that minimizes the overhead associated with maintaining a sorted list with a large number of events.

1.1.1 Model Time

In the DE model of computation, time is *global*, in the sense that all actors share the same global time. The *current time* of the model is often called the *model time* or *simulation time* to avoid confusion with current real time.

As in most Ptolemy II domains, actors communicate by sending tokens through ports. Ports can be input ports, output ports, or both. Tokens are sent by an output port and received by all input ports connected to the output port through relations. When a token is sent from an output port, it is packaged as an event and stored in a global event queue. By default, the time stamp of an output is the model time, although specialized DE actors can produce events with future time stamps.

Actors may also request that they be fired now, or at some time in the future, by calling the fireAtCurrentTime(), fireAt(), or fireAtRelativeTime() methods of the director. Each of these places a *pure*

event (one with a time stamp, but no data) on the event queue. A pure event can be thought of as setting an alarm clock to be awakened in the future. Sources (actors with no inputs) are thus able to be fired despite having no inputs to trigger a firing. Moreover, actors that introduce *delay* (outputs have larger time stamps than the inputs) can use this mechanism to schedule a firing in the future to produce an output. The fireAtCurrentTime() method provides a mechanism for achieving a *zero delay* by atomically getting the current model time and queuing an event with that time stamp. This permits I/O actors to have themselves fired in real-time whenever data arrives at a physical I/O port.

In the global event queue, events are sorted based on their time stamps. An event is removed from the global event queue when the *model time* reaches its time stamp, and if it has a data token, then that token is put into the destination input port.

At any point in the execution of a model, the events stored in the global event queue have time stamps greater than or equal to the model time. The DE director is responsible for advancing (i.e. incrementing) the model time when all events with time stamps equal to the current model time have been processed (i.e. the global event queue only contains events with time stamps strictly greater than the current time). The current time is advanced to the smallest time stamp of all events in the global event queue.

1.1.2 Simultaneous events

An important aspect of a DE domain is the prioritizing of simultaneous events. This gives the domain a dataflow-like behavior for events with identical time stamps. It is done by assigning a *depth* to each actor and a *microstep* to each phase of execution within a given time stamp. Each depth is a non-negative integer, uniquely assigned; i.e. no two actors are assigned the same depth.

The depth of an actor determines the *priority* of events destined to that actor, relative to other events with the same time stamp and the same microstep. The highest priority events are those destined to actors with the lowest depth.

Consider the simple topology shown in figure 1.1. Assume that actor *Y* is not a delay actor, meaning that its output events have the same time stamp and microstep as its input events (this is suggested by the dotted arrow). Suppose that actor *X* produces an event with time stamp τ. That event is available at ports *B* and *D*, so the scheduler could choose to fire actors *Y* or *Z*. Which should it fire? Intuition tells us it should fire the upstream one first, *Y*, because that firing may produce another event with time stamp τ at port *D* (which is presumably a multiport). It seems logical that if actor *Z* is going to get one event on each input channel with the same time stamp, then it should see those events in the same firing. Thus, if there are simultaneous events at *B* and *D*, then the one at *B* will have higher priority.

The depths are determined by a *topological sort* of a *directed acyclic graph* (DAG) of the actors. The DAG of actors follows the topology of the graph, except when there are declared delays. Once the DAG is constructed, it is sorted topologically. This simply means that an ordering of actors is assigned

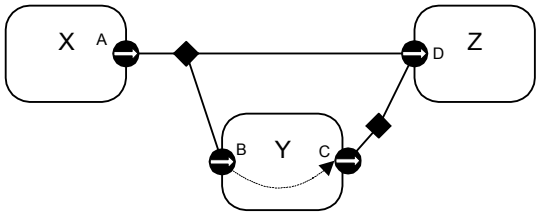


FIGURE 1.1. If there are simultaneous events at B and D, then the one at B will have higher priority because it may trigger another simultaneous event at D.

such that an upstream actor in the DAG is earlier in the ordering than a downstream actor. The depth of an actor is defined to be its position in this topological sort, starting with zero. For example, in figure 1.1, *X* will have depth 0, *Y* will have depth 1, and *Z* will have depth 2.

In general, a DAG has several correct topological sorts. The topological sort is not unique, meaning that the depths assigned to actors are somewhat arbitrary. But an upstream actor will always have a lower depth than a downstream actor, unless there is an intervening delay actor. Thus, given simultaneous input events with the same microstep, an upstream actor will always fire before a downstream actor. Such a strategy ensures that the execution is *deterministic*, assuming the actors only communicate via events. In other words, even though there are several possible choices that a scheduler could make for an ordering of firings, all choices that respect the priorities yield the same results.

There are situations where constructing a DAG following the topology is not possible. Consider the topology shown in figure 1.2. It is evident from the figure that the topology is not acyclic. Indeed, figure 1.2 depicts a *zero-delay loop* where topological sort cannot be done. The director will refuse to run the model, and will terminate with an error message.

The TimedDelay actor in DE is a domain-specific actor that asserts a delay relationship between its input and output. Thus, if we insert a TimedDelay actor in the loop, as shown in figure 1.3, then constructing the DAG becomes once again possible. The TimedDelay actor breaks the precedences.

Note in particular that the TimedDelay actor breaks the precedences *even if its delay parameter is set to zero*. Thus, the DE domain is perfectly capable of modeling feedback loops with zero time delay, but the model builder has to specify the order in which events should be processed by placing a TimedDelay actor with a zero value for its parameter. When modeling multiple zero-delay feedback paths, simultaneity of the fed back signals is modeled by having the same number of TimedDelay actors in each feedback path.

1.1.3 Iteration

At each iteration, after advancing the current time, the director chooses all events in the global event queue that have the smallest time stamps, microstep, and depth (tested in that order). The chosen events are then removed from the global event queue and their data tokens are inserted into the appro-

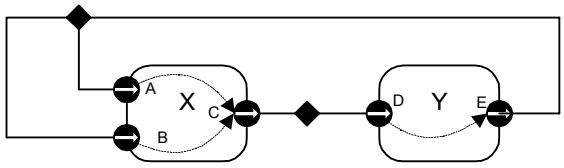


FIGURE 1.2. An example of a directed zero-delay loop.

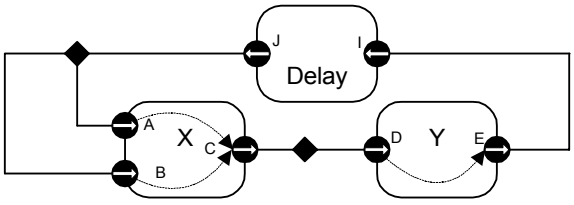


FIGURE 1.3. A Delay actor can be used to break a zero-delay loop.

priate input ports of the destination actor. Then, the director iterates the destination actor; i.e. it invokes prefire(), fire(), and postfire(). All of these events are destined to the same actor, since the depth is unique for each actor.

A firing may produce additional events at the current model time (the actor reacts *instantaneously*, or has *zero delay*). There also may be other events with time stamp equal to the current model time still pending on the event queue. The DE director repeats the above procedure until there are no more events with time stamp equal to the current time. This concludes one iteration of the model. An iteration, therefore, processes all events on the event queue with the smallest time stamp.

1.1.4 Getting a Model Started

Before one of the iterations described above can be run, there have to be initial events in the global event queue. Actors may produce initial pure events or regular output events in their initialize() method. Thus, to get a model started, at least one actor must produce events. All the domain-polymorphic timed sources described in the Actor Libraries chapter produce pure events, so these can be used in DE. We can define the *start time* to be the smallest time stamp of these initial events.

1.1.5 Pure Events at the Current Time

An actor calls fireAt() to schedule a pure event. The pure event is a request to the scheduler to fire the actor sometime in the future. However, the actor may choose to call fireAt() with the time argument equal to the current time. In fact, the preferred method for domain-polymorphic source actors to get started is to have code like the following in their initialize() method:

```
Director director = getDirector();
director.fireAt(this, director.getCurrentTime());
```

This will schedule a pure event on the event queue with microstep zero and depth equal to that of the calling actor.

An actor may also call fireAt() with the current time in its fire() method. This is a request to be refired later *in the current iteration*. This is managed by queueing a pure event with microstep one greater than the current microstep. In fact, this is the only situation in which the microstep is incremented beyond zero.

A pure event at the current time can also be scheduled by code like the following:

```
Director director = getDirector();
director.fireAtCurrentTime(this);
```

This code is equivalent to the previous example when used within standard actor methods like initialize() and fire(). This is because the director never advances model time while an actor is being initialized or fired. However, when methods (such as an I/O callback) queue events at the current time, they need to use the latter code. This is because the director runs in a separate thread from the callback and, in the former code, will occasionally advance the model time between the call to getCurrentTime() and the call to fireAt().

1.1.6 Stopping Execution

Execution stops when one of these conditions become true:

- The current time reaches the *stop time*, set by calling the setStopTime() method of the DE director.
- The global event queue becomes empty and the *stopWhenQueueIsEmpty* parameter of the director is true.

Events at the stop time are processed before stopping the model execution. The execution ends by calling the wrapup() method of all actors. Wrapup() is called even when execution has been stopped due to an exception. Therefore, throwing an exception in the wrapup() method of an actor is not recommended as this exception will mask the original exception, making the source of the original exception difficult to locate.

It is also possible to explicitly invoke the iterate() method of the manager for some fixed number of iterations. Recall that an iteration processes all events with a given time stamp, so this will run the model through a specified number of discrete time steps.

Note that an actor can prevent execution from stopping properly if it blocks in its fire() method. An actor which blocks in fire() should have a stopFire() method which, when called, notifies the fire() method to cease blocking and return.

1.2 Overview of The Software Architecture

The UML static structure diagram for the DE kernel package is shown in figure 1.4. For model builders, the important classes are DEDirector, DEActor and DEIOPort. At the heart of DEDirector is a global event queue that sorts events according to their time stamps and priorities.

The DEDirector uses an efficient implementation of the global event queue, a calendar queue data structure [17]. In theory, the time complexity for this particular implementation is O(1) in both enqueue and dequeue operations. This means that the time complexity for enqueue and dequeue operations is independent of the number of pending events in the global event queue. However, to realize this performance, it is necessary for the distribution of events to match certain assumptions. Our calendar queue implementation observes events as they are dequeued and adapts the structure of the queue according to their statistical properties. Nonetheless, the calendar queue structure will not prove optimal for all models. For extensibility, alternative implementations of the global event queue can be realized by implementing the DEEventQueue interface and specifying the event queue using the appropriate constructor for DEDirector.

The DEEvent class carries tokens through the event queue. It contains their time stamp, their microstep, and the depth of the destination actor, as well as a reference to the destination actor. It implements the java.lang.Comparable interface, meaning that any two instances of DEEvent can be compared. The private inner class DECQEventQueue.DECQComparator, which is provided to the calendar queue at the time of its construction, performs the requisite comparisons of events.

The DEActor class provides convenient methods to access time, since time is an essential part of a timed domain like DE. Nonetheless, actors in a DE model are not required to be derived from the DEActor class. Simply deriving from TypedAtomicActor gives you the same capability, but without the convenience. In the latter case, time is accessible through the director.

The DEIOPort class is be used by actors that are specialized to the DE domain. It supports annotations that inform the scheduler about delays through the actor. It also provides two additional methods, overloaded versions of broadcast() and send(). The overloaded versions have a second argument for the time delay, allowing actors to send output data with a time delay (relative to current time).

Domain polymorphic actors, such as those described in the Actor Libraries chapter, have as ports

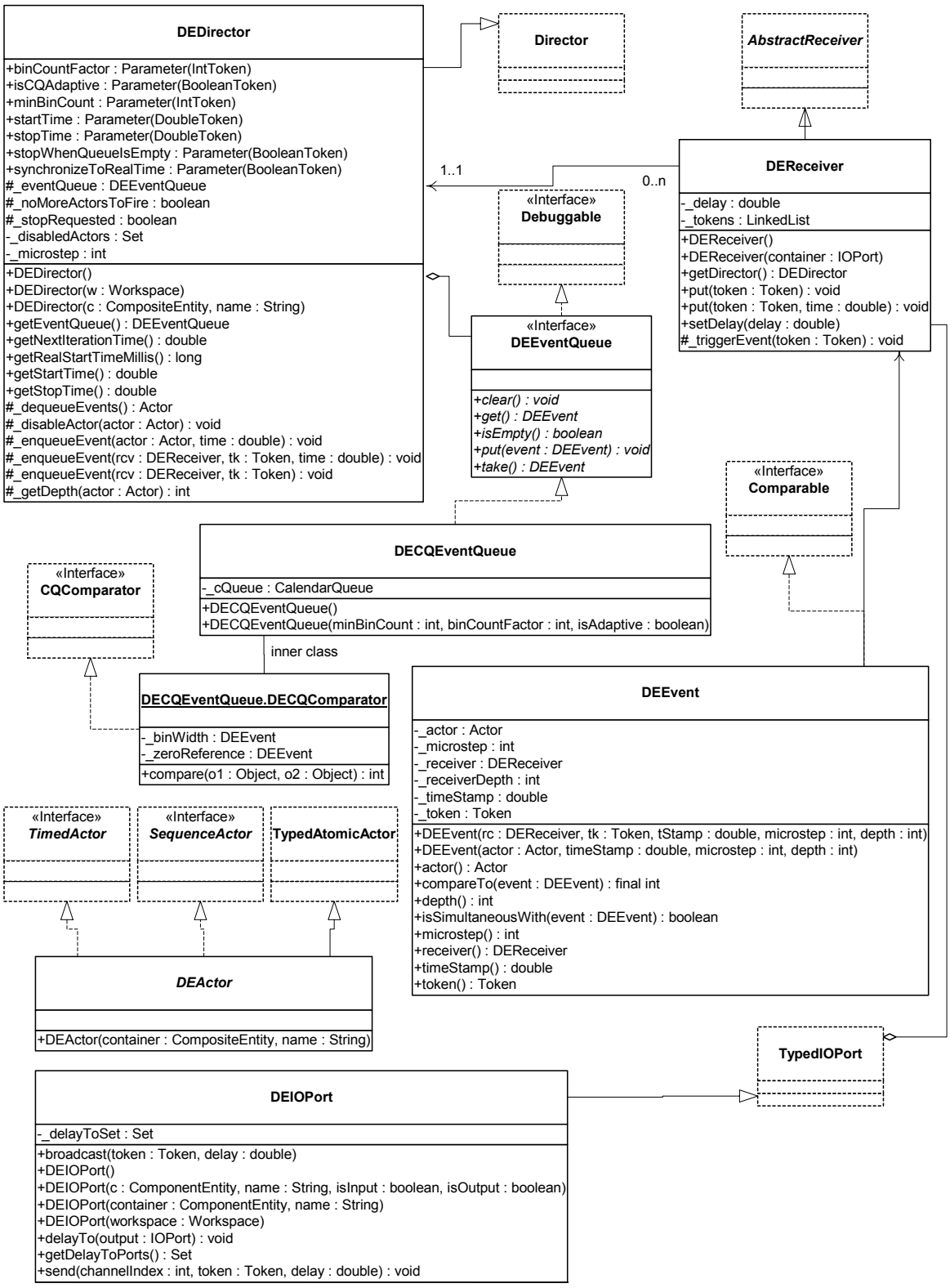


FIGURE 1.4. UML static structure diagram for the DE kernel package.

instances of TypedIOPort, not DEIOPort, and therefore cannot produce events in the future directly by sending it through output ports. Note that tokens sent through TypedIOPort are treated as if they were sent through DEIOPort with the time delay argument equal to zero. Domain polymorphic actors can produce events in the future indirectly by using the fireAt() and fireAtRelativeTime() methods of the director. By calling fireAt() or fireAtRelativeTime(), the actor requests a refiring in the future. The actor can then produce a delayed event during the refiring.

1.3 The DE Actor Library

The DE domain has a small library of actors in the ptolemy.domains.de.lib package, shown in figure 1.5. These actors are particularly characterized by implementing both the TimedActor and SequenceActor interfaces. These actors use the current model time, and in addition, assume they are dealing with sequences of discrete events. Some of them use domain-specific infrastructure, such as the convenience class DEActor and the base class DETransformer. The DETransformer class provides an input and output port that are instances of DEIOPort. The Delay and Server actors use facilities of these ports to influence the firing priorities. The Merge actor merges events sequences in chronological order.

1.4 Mutations

The DE director tolerates changes to the model during execution. The change should be queued using requestChange(). While invoking those changes, the method invalidateSchedule() is expected to be called, notifying the director that the topology it used to calculate the priorities of the actors is no longer valid. This will result in the priorities being recalculated the next time prefire() is invoked.

An example of a mutation is shown in figures 1.6 and 1.7. Figure 1.7 defines a class that constructs a simple model in its constructor. The model consists of a clock connected to a recorder. The method insertClock() creates an anonymous inner class that extends ChangeRequest. Its execute() method disconnects the two existing actors, creates a new clock and a merge actor, and reconnects the actors as shown in figure 1.6.

When the insertClock() method is called, a change request is queue with the top-level composite actor, which delegates the request to the manager. The manager executes the request after the current iteration completes. Thus, the change will always be executed between non-equal time stamps, since an iteration consists of processing all events at the current time stamp.

Actors that are added in the change request are automatically initialized. Note, however, one sub-

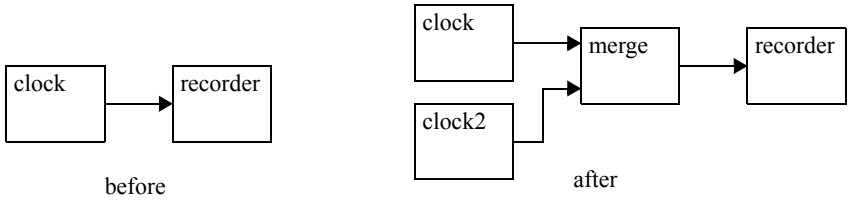


FIGURE 1.6. Topology before and after mutation for the example in figure 1.7.

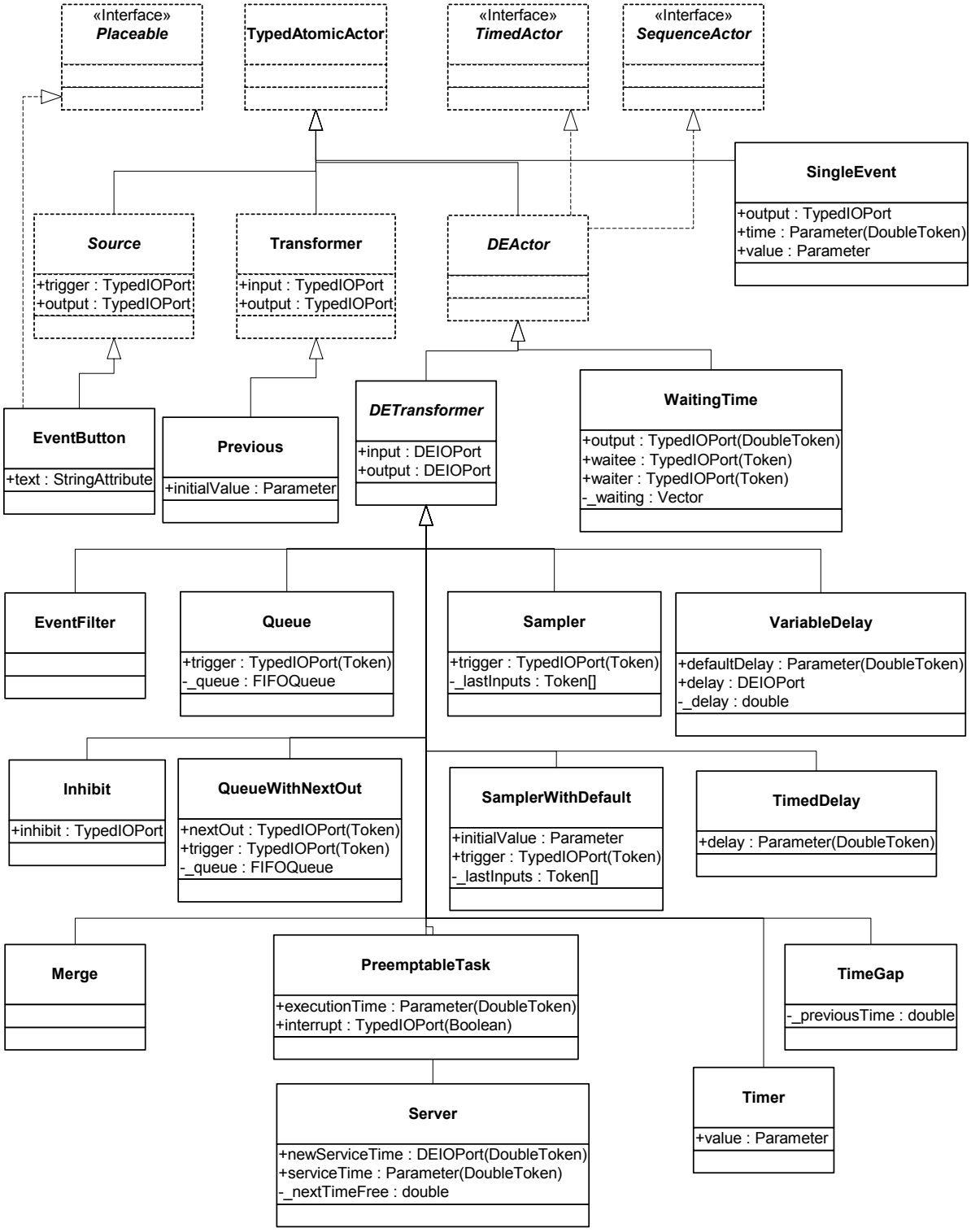


FIGURE 1.5. The library of DE-specific actors.

tlety. The next to last line of the insertClock() method is:

```
_rec.input.createReceivers();
```

```
package ptolemy.domains.de.lib.test;

import ptolemy.kernel.util.*;
import ptolemy.kernel.*;
import ptolemy.actor.*;
import ptolemy.actor.lib.*;
import ptolemy.domains.de.kernel.*;
import ptolemy.domains.de.lib.*;

public class Mutate {

    public Manager manager;

    private Recorder _rec;
    private Clock _clock;
    private TypedCompositeActor _top;
    private DEDirector _director;

    public Mutate() throws IllegalActionException,
            NameDuplicationException {
       _top = new TypedCompositeActor();
       _top.setName("top");
       manager = new Manager();
       _director = new DEDirector();
       _top.setDirector(_director);
       _top.setManager(manager);

       _clock = new Clock(_top, "clock");
       _clock.values.setExpression("[1.0]");
       _clock.offsets.setExpression("[0.0]");
       _clock.period.setExpression("1.0");
       _rec = new Recorder(_top, "recorder");
       _top.connect(_clock.output, _rec.input);
    }

    public void insertClock() {
       // Create an anonymous inner class
       ChangeRequest change = new ChangeRequest(_top, "test2") {
          public void _execute() throws IllegalActionException,
                 NameDuplicationException {
             _clock.output.unlinkAll();
             _rec.input.unlinkAll();
             Clock clock2 = new Clock(_top, "clock2");
             clock2.values.setExpression("[2.0]");
             clock2.offsets.setExpression("[0.5]");
             clock2.period.setExpression("2.0");
             Merge merge = new Merge(_top, "merge");
             _top.connect(_clock.output, merge.input);
             _top.connect(clock2.output, merge.input);
             _top.connect(merge.output, _rec.input);
             // Any pre-existing input port whose connections
             // are modified needs to have this method called.
             _rec.input.createReceivers();
             _director.invalidateSchedule();
          }
       };
       _top.requestChange(change);
    }
}
```

FIGURE 1.7. An example of a class that constructs a model and then mutates it.

This method call is necessary because the connections of the recorder actor have changed, but since the actor is not new, it will *not* be reinitialized. Recall that the preinitialize() and initialize() methods are guaranteed to be called only once, and one of the responsibilities of the preinitialize() method is to create the receivers in all the input ports of an actor. Thus, whenever connections to an input port change during a mutation, the mutation code itself must call createReceivers() to reconstruct the receivers. Note that this will result in the loss of any tokens that might already be queued in the preexisting receivers of the ports. It is because of this possible loss of data that the creation of receivers is not done automatically. The designer of the mutation should be aware of the possible loss of data.

There are two additional subtleties about mutations. One involves events left on the queue and the other involves locked resources.

If an actor produces events in the future via DEIOPort, then the destination actor will be fired even if it has been removed from the topology by the time the execution reaches that future time. This may not always be the expected behavior. The Delay actor in the DE library behaves this way, so if its destination is removed before processing delayed events, then it may be invoked at a time when it has no container. Most actors will tolerate this and will not cause problems. But some might have unexpected behavior. To prevent this behavior, the mutation that removes the actor should also call the disableActor() method of the director.

If an actor locks a resource, such as an I/O port or DatagramSocket, it typically releases this resource in its wrapup() method. However, when the actor is removed while the model is executing, wrapup() never gets called. This case can be handled by overriding the setContainer() method with the following code:

```
public void setContainer(CompositeEntity container)
          throws IllegalActionException, NameDuplicationException {
     if (container != getContainer()) {
       wrapup();
     }
   super.setContainer(container);
}
```

When overriding setContainer() in this way, it is best to make wrapup() idem potent because future implementations of the director might automatically unlock resources of removed actors.

1.5 Writing DE Actors

It is very common in DE modeling to include custom-built actors. No pre-defined actor library seems to prove sufficient for all applications. For the most part, writing actors for the DE domain is no different than writing actors for any other domain. Some actors, however, need to exercise particular control over time stamps and actor priorities. Such actors use instances of DEIOPort rather than TypedIOPort. The first section below gives general guidelines for writing DE actors and domain-polymorphic actors that work in DE. The second section explains in detail the priorities, and in particular, how to write actors that declare delays. The final section discusses actors that operate as a Java thread.

1.5.1 General Guidelines

The points to keep in mind are:

- When an actor fires, not all ports have tokens, and some ports may have more than one token. The time stamps of the events that contained these tokens are no longer explicitly available. The current model time is assumed to be the time stamp of the events.
- If the actor leaves unconsumed tokens on its input ports, then it will be iterated again before model time is advanced. This ensures that the current model time is in fact the time stamp of the input events. However, occasionally, an actor will want to leave unconsumed tokens on its input ports, and not be fired again until there is some other new event to be processed. To get this behavior, it should return *false* from prefire(). This indicates to the DE director that it does not wish to be iterated.
- If the actor returns *false* from postfire(), then the director will not fire that actor again. Events that are destined for that actor are discarded.
- When an actor produces an output token, the time stamp for the output event is taken to be the current model time. If the actor wishes to produce an event at a future model time, one way to accomplish this is to call the director's fireAt() method to schedule a future firing, and then to produce the token at that time. A second way to accomplish this is to use instances of DEIOPort and use the overloaded send() or broadcast() methods that take a time delay argument.
- If an actor contains a callback method or a private thread (as opposed to the public run() method of the Thread Actor discussed in section 14.5.3), and this callback or thread wishes to produce an event now or at a future model time, then a reliable way to achieve this is to call either the fireAtCurrentTime() method or the fireAtRelativeTime() method. These methods may safely be called asynchronously, yielding real-time liveness. By contrast, fireAt() must be called from within a standard actor method.
- The DEIOPort class (see figure 1.4) can produce events in the future, but there is an important subtlety with using these methods. Once an event has been produced, it cannot be retracted. In particular, even if the actor which produced the event (or the destination actor of the event) is deleted before model time reaches that of the future event, the event will be delivered to the destination. If you use fireAt(), fireAtCurrentTime(), or fireAtRelativeTime() instead to generate delayed events, then if the actor is deleted (or returns *false* from postfire()) before the future event, then the future event will not be produced.
- By convention in Ptolemy II, actors update their state only in the postfire() method. In DE, the fire() method is only invoked once per iteration, so there is no particular reason to stick to this convention. Nonetheless, we recommend that you do in case your actor becomes useful in other domains. The simplest way to ensure this is follow the following pattern. For each state variable, such as a private variable named *_count*,

```
private int _count;
```

create a shadow variable

```
private int _countShadow;
```

Then write the methods as follows:

```
public void fire() {
   _countShadow = _count;
   ... perform some computation that may modify _countShadow ...
}
public boolean postfire() {
   _count = _countShadow;
   return super.postfire();
}
```

This ensures that the state is updated only in postfire().

In a similar fashion, delayed outputs (produced by either mechanism) should be produced only in the postfire() method, since a delayed outputs are persistent state. Thus, fireAt() should be called in postfire() only, as should the overloaded send() and broadcast() of DEIOPort.

1.5.2 Examples

Simplified Delay Actor. An example of a domain-specific actor for DE is shown in figure 1.8. This actor delays input events by some amount specified by a parameter. The domain-specific features of the actor are shown in bold. They are:

- It uses DEIOPort rather than TypedIOPort.
- It has the statement:

```
input.delayTo(output);
```

  This statement declares to the director that this actor implements a delay from input to output. The director uses this to break the precedences when constructing the DAG to find priorities.
- It uses an overloaded send() method, which takes a delay argument, to produce the output. Notice that the output is produced in the postfire() method, since by convention in Ptolemy II, persistent state is not updated in the fire() method, but rather is updated in the postfire() method.

Server Actor. The Server actor in the DE library (see figure 1.5) uses a rich set of behavioral properties of the DE domain. A server is a process that takes some amount of time to serve "customers." While it is serving a customer, other arriving customers have to wait. This actor can have a fixed service time (set via the parameter *serviceTime*, or a variable service time, provided via the input port *newServiceTime*). A typical use would be to supply random numbers to the *newServiceTime* port to generate random service times. These times can be provided at the same time as arriving customers to get an effect where each customer experiences a different, randomly selected service time.

The (compacted) code is shown in figure 1.9. This actor extends DETransformer, which has two public members, *input* and *output*, both instances of DEIOPort. The constructor makes use of the delayTo() method of these ports to indicate that the actor introduces delay between its inputs and its output.

The actor keeps track of the time at which it will next be free in the private variable _nextTimeFree. This is initialized to minus infinity to indicate that whenever the model begins executing, the server is free. The prefire() method determines whether the server is free by comparing this private variable against the current model time. If it is free, then this method returns true, indicating to

the scheduler that it can proceed with firing the actor. If the server is not free, then the prefire() method checks to see whether there is a pending input, and if there is, requests a firing when the actor will become free. It then returns false, indicating to the scheduler that it does not wish to be fired at this time. Note that the prefire() method uses the methods getCurrentTime() and fireAt() of DEActor, which are simply convenient interfaces to methods of the same name in the director.

The fire() method is invoked only if the server is free. It first checks to see whether the newServiceTime port is connected to anything, and if it is, whether it has a token. If it does, the token is read and used to update the *serviceTime* parameter. No more than one token is read, even if there are more in the input port, in case one token is being provided per pending customer.

The fire() method then continues by reading an input token, if there is one, and updating _nextTimeFree. The input token that is read is stored temporarily in the private variable _currentInput. The postfire() method then produces this token on the output port, with an appropriate delay. This is done in the postfire() method rather than the fire() method in keeping with the policy in Ptolemy II that persistent state is not updated in the fire() method. Since the output is produced with a future time stamp, then it is persistent state.

Note that when the actor will not get input tokens that are available in the fire() method, it is essen-

```
package ptolemy.domains.de.lib.test;

import ptolemy.actor.TypedAtomicActor;
import ptolemy.domains.de.kernel.DEIOPort;
import ptolemy.data.DoubleToken;
import ptolemy.data.Token;
import ptolemy.data.expr.Parameter;
import ptolemy.actor.TypedCompositeActor;
import ptolemy.kernel.util.IllegalActionException;
import ptolemy.kernel.util.NameDuplicationException;
import ptolemy.kernel.util.Workspace;

public class SimpleDelay extends TypedAtomicActor {

    public SimpleDelay(TypedCompositeActor container, String name)
            throws NameDuplicationException, IllegalActionException  {
        super(container, name);
        input = new DEIOPort(this, "input", true, false);
        output = new DEIOPort(this, "output", false, true);
        delay = new Parameter(this, "delay", new DoubleToken(1.0));
        delay.setTypeEquals(DoubleToken.class);
        input.delayTo(output);
    }

    public Parameter delay;
    public DEIOPort input;
    public DEIOPort output;
    private Token _currentInput;

    public void fire() throws IllegalActionException {
        _currentInput = input.get(0);
    }

    public boolean postfire() throws IllegalActionException {
        output.send(0, _currentInput,
                ((DoubleToken)delay.getToken()).doubleValue());
        return super.postfire();
    }
}
```

FIGURE 1.8. A domain-specific actor in DE.

```
package ptolemy.domains.de.lib;
import statements ...
public class Server extends DETransformer {

   public DEIOPort newServiceTime;
   public Parameter serviceTime;

   private Token _currentInput;
   private double _nextTimeFree = Double.NEGATIVE_INFINITY;

   public Server(TypedCompositeActor container, String name)
           throws NameDuplicationException, IllegalActionException  {
        super(container, name);
        serviceTime = new Parameter(this, "serviceTime", new DoubleToken(1.0));
        serviceTime.setTypeEquals(BaseType.DOUBLE);
        newServiceTime = new DEIOPort(this, "newServiceTime", true, false);
        newServiceTime.setTypeEquals(BaseType.Double);
        output.setTypeAtLeast(input);
        input.delayTo(output);
        newServiceTime.delayTo(output);
    }

   ... attributeChanged(), clone() methods ...

   public void initialize() throws IllegalActionException {
        super.initialize();
        _nextTimeFree = Double.NEGATIVE_INFINITY;
   }

   public boolean prefire() throws IllegalActionException {
      DEDirector director = (DEDirector)getDirector();DEDirector dir = (DEDirector)getDirector();

      if (director.getCurrentTime() >= _nextTimeFree) {
           return true;
       } else {
           // Schedule a firing if there is a pending token so it can be served.
           if (input.hasToken(0)) {
               director.fireAt(this,_nextTimeFree);
           }
           return false;
       }
    }

   public void fire() throws IllegalActionException {
        if (newServiceTime.getWidth() > 0 && newServiceTime.hasToken(0)) {
            DoubleToken time = (DoubleToken)(newServiceTime.get(0));
            serviceTime.setToken(time);
        }
        if (input.getWidth() > 0 && input.hasToken(0)) {
            _currentInput = input.get(0);
            double delay = ((DoubleToken)serviceTime.getToken()).doubleValue();
            _nextTimeFree = ((DEDirector)getDirector()).getCurrentTime() + delay;
        } else {
            _currentInput = null;
        }
   }

   public boolean postfire() throws IllegalActionException {
        if (_currentInput != null) {
            double delay = ((DoubleToken)serviceTime.getToken()).doubleValue();
            output.send(0, _currentInput, delay);
        }
        return super.postfire();
   }
}
```

FIGURE 1.9. Code for the Server actor. For more details, see the source code.

tial that prefire() return false. Otherwise, the DE scheduler will keep firing the actor until the inputs are all consumed, which will never happen if the actor is not consuming inputs!

Like the SimpleDelay actor in figure 1.8, this one produces outputs with future time stamps, using the overloaded send() method of DEIOPort that takes a delay argument. There is a subtlety associated with this design. If the model mutates during execution, and the Server actor is deleted, it cannot retract events that it has already sent to the output. Those events will be seen by the destination actor, even if by that time neither the server nor the destination are in the topology! This could lead to some unexpected results, but hopefully, if the destination actor is no longer connected to anything, then it will not do much with the token.

1.5.3 Thread Actors

In some cases, it is useful to describe an actor as a thread that waits for input tokens on its input ports. The thread suspends while waiting for input tokens and is resumed when some or all of its input ports have input tokens. While this description is functionally equivalent to the standard description explained above, it leverages on the Java multi-threading infrastructure to save the state information.

Consider the code for the ABRecognizer actor shown in figure 1.10. The two code listings implement two actors with equivalent behavior. The left one implements it as a threaded actor, while the right one implements it as a standard actor. We will from now on refer to the left one as the threaded description and the right one as the standard description. In both descriptions, the actor has two input ports, `inportA` and `inportB`, and one output port, `outport`. The behavior is as follows.

> *Produce an output event at outport as soon as events at inportA and inportB occurs in that particular order, and repeat this behavior.*

Note that the standard description needs a state variable `state`, unlike the case in the threaded description. In general the threaded description encodes the state information in the position of the code, while the standard description encodes it explicitly using state variables. While it is true that the

```
public class ABRecognizer extends DEThreadActor {
    StringToken msg = new StringToken("Seen AB");

    // the run method is invoked when the thread
    // is started.
    public void run() {
        while (true) {
            waitForNewInputs();
            if (inportA.hasToken(0)) {
                IOPort[] nextInport = {inportB};
                waitForNewInputs(nextInport);
                outport.broadcast(msg);
            }
        }
    }
```

```
public class ABRecognizer extends DEActor {
    StringToken msg = new StringToken("Seen AB");

    // We need an explicit state variable in
    // this case.
    int state = 0;

    public void fire() {
        switch (state) {
            case 0:
                if (inportA.hasToken(0)) {
                    state = 1;
                    break;
                }
            case 1:
                if (inportB.hasToken(0)) {
                    state = 0;
                    outport.broadcast(msg);
                }
        }
    }
}
```

FIGURE 1.10. Code listings for two style of writing the ABRecognizer actor.

context switching overhead associated with multi-threading application reduces the performance, we argue that the simplicity and clarity of writing actors in the threaded fashion is well worth the cost in some applications.

The infrastructure for this feature is shown in figure 1.4. To write an actor in the threaded fashion, one simply derives from the DEThreadActor class and implements the run() method. In many cases, the content of the run() method is enclosed in the infinite '`while(true)`' loop since many useful threaded actors do not terminate.

The waitForNewInputs() method is overloaded and has two flavors, one that takes no arguments and another that takes an IOPort array as argument. The first suspends the thread until there is at least one input token in at least one of the input ports, while the second suspends until there is at least one input token in any one of the specified input ports, ignoring all other tokens.

In the current implementation, both versions of waitForNewInputs() clear all input ports before the thread suspends. This guarantees that when the thread resumes, all tokens available are new, in the sense that they were not available before the waitForNewInput() method call.

The implementation also guarantees that between calls to the waitForNewInputs() method, the rest of the DE model is suspended. This is equivalent to saying that the section of code between calls to the waitForNewInput() method is a critical section. One immediate implication is that the result of the method calls that check the configuration of the model (e.g. hasToken() to check the receiver) will not be invalidated during execution in the critical section. It also means that this should not be viewed as a way to get parallel execution in DE. For that, consider the DDE domain.

It is important to note that the implementation serializes the execution of threads, meaning that at any given time there is only one thread running. When a threaded actor is running (i.e. executing inside its run() method), all other threaded actors and the director are suspended. It will keep running until a waitForNewInputs() statement is reached, where the flow of execution will be transferred back to the director. Note that the director thread executes all non-threaded actors. This serialization is needed because the DE domain has a notion of global time, which makes parallelism much more difficult to achieve.

The serialization is accomplished by the use of monitor in the DEThreadActor class. Basically, the fire() method of the DEThreadActor class suspends the calling thread (i.e. the director thread) until the threaded actor suspends itself (by calling waitForNewInputs()). One key point of this implementation is that the threaded actors appear just like an ordinary DE actor to the DE director. The DEThreadActor base class encapsulates the threaded execution and provides the regular interfaces to the DE director. Therefore the threaded description can be used whenever an ordinary actor can, which is everywhere.

The code shown in figure 1.11 implements the run method of a slightly more elaborate actor with the following behavior:

> *Emit an output O as soon as two inputs A and B have occurred. Reset this behavior each time the input R occurs.*

Recent work has extended the DE Director to support parallel execution in the form of actors containing private threads and callbacks. Future work in this area may involve extending the infrastructure to support additional concurrency constructs, such as preemption, other forms of parallel execution, etc. It might also be interesting to explore new concurrency semantics similar to the threaded DE, but without the 'forced' serialization.

1.6 Composing DE with Other Domains

One of the major concepts in Ptolemy II is modeling heterogeneous systems through the use of hierarchical heterogeneity. Actors on the same level of hierarchy obey the same set of semantics rules. Inside some of these actors may be another domain with a different model of computation. This mechanism is supported through the use of opaque composite actors. An example is shown in figure 1.12. The outermost domain is DE and it contains seven actors, two of them are opaque and composite. The opaque composite actors contain subsystems, which in this case are in the DE and CT domains.

1.6.1 DE inside Another Domain

The DE subsystem completes one iteration whenever the opaque composite actor is fired by the

```
public void run() {
    try {
        while (true) {
            // In initial state..
            waitForNewInputs();
            if (R.hasToken(0)) {
                // Resetting..
                continue;
            }
            if (A.hasToken(0)) {
                // Seen A..
                IOPort[] ports = {B,R};
                waitForNewInputs(ports);
                if (!R.hasToken(0)) {
                    // Seen A then B..
                    O.broadcast(new DoubleToken(1.0));
                    IOPort[] ports2 = {R};
                    waitForNewInputs(ports2);
                } else {
                    // Resetting
                    continue;
                }
            } else if (B.hasToken(0)) {
                // Seen B..
                IOPort[] ports = {A,R};
                waitForNewInputs(ports);
                if (!R.hasToken(0)) {
                // Seen B then A..
                O.broadcast(new DoubleToken(1.0));
                IOPort[] ports2 = {R};
                waitForNewInputs(ports2);
            } else {
                // Resetting
                continue;
            }
        } // while (true)
    } catch (IllegalActionException e) {
        getManager().notifyListenersOfException(e);
    }
}
```

FIGURE 1.11. The run() method of the ABRO actor.

outer domain. One of the complications in mixing domains is in the synchronization of time. Denote the current time of the DE subsystem by t_{inner} and the current time of the outer domain by t_{outer}. An iteration of the DE subsystem is similar to an iteration of a top-level DE model, except that prior to the iteration tokens are transferred from the ports of the opaque composite actors into the ports of the contained DE subsystem, and after the end of the iteration, the director requests a refire at the smallest time stamp in the event queue of the DE subsystem. This presumes that the DE subsystem knows at what time stamp the it, or one of its contained actors, will wish to be refired. Future work may remove this limitation, allowing real-time events (such as from I/O) to propagate out of a DE subsystem. Currently the DE domain can handle such asynchronous events only if it is not inside another domain.

The transfer of tokens from the ports of the opaque composite actor into the ports of the contained DE subsystem actors is done in the transferInputs() method of the DE director. This method is extended from its default implementation in the Director class. The implementation in the DEDirector class advances the current time of the DE subsystem to the current time of the outer domain, then calls super.transferInputs(). It is done in order to correctly associate tokens seen at the input ports of the opaque composite actor, if any, with events at the current time of the outer domain, t_{outer}, and put these events into the global event queue. This mechanism is, in fact, how the DE subsystem synchronize its current time, t_{inner}, with the current time of the outer domain, t_{outer}.(Recall that the DE director advances time by looking at the smallest time stamp in the event queue of the DE subsystem). Specifically, before the advancement of the current time of the DE subsystem t_{inner} is less than or equal to the t_{outer}, and after the advancement t_{inner} is equal to the t_{outer}.

Requesting a refiring is done in the postfire() method of the (inner) DE director by calling the fireAt() method of the executive (outer) director. Its purpose is to ensure that events in the DE sub-

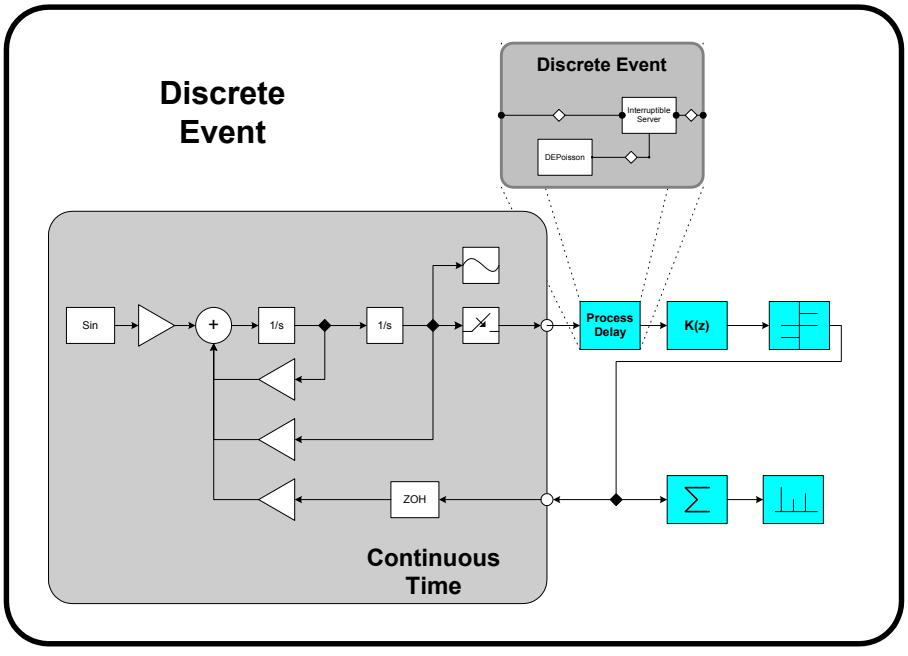


FIGURE 1.12. An example of heterogeneous and hierarchical composition. The CT subsystem and DE subsystem are inside an outermost DE system. This example is developed by Jie Liu [81].

system are processed on time with respect to the current time of the outer domain, t_{outer}.

Note that if the DE subsystem is fired due to the outer domain processing a refire request, then there may not be any tokens in the input port of the opaque composite actor at the beginning of the DE subsystem iteration. In that case, no new events with time stamps equal to t_{outer} will be put into the global event queue. Interestingly, in this case, the time synchronization will still work because t_{inner} will be advanced to the smallest time stamp in the global event queue which, in turn, has to equal t_{outer} because we always request a refire according to that time stamp.

1.6.2 Another Domain inside DE

Due to its nature, any opaque composite actor inside DE is opaque and therefore, as far as the DE Director is concerned, behaves exactly like a domain polymorphic actor. Recall that domain polymorphic actors are treated as functions with zero delay in computation time. To produce events in the future, domain polymorphic actors request a refire from the DE director and then produce the events when it is refired.

2

CT Domain

Author: *Jie Liu*

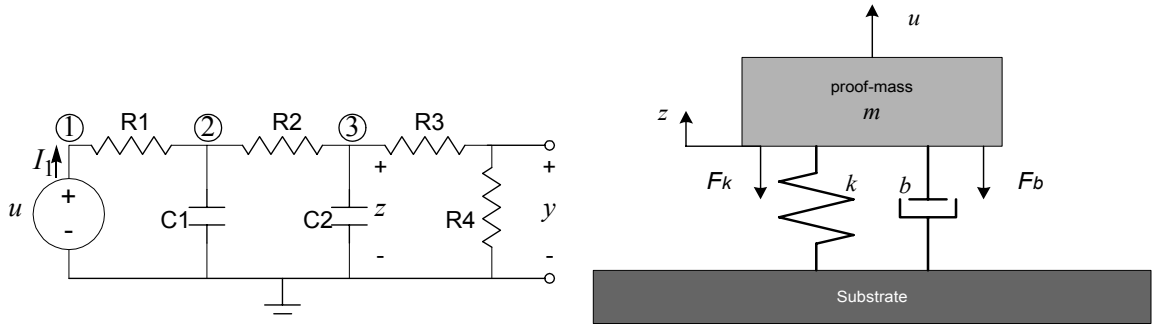
2.1 Introduction

The continuous-time (CT) domain in Ptolemy II aims to help the design and simulation of systems that can be modeled using ordinary differential equations (ODEs). ODEs are often used to model analog circuits, plant dynamics in control systems, lumped-parameter mechanical systems, lumped-parameter heat flows and many other physical systems.

Let's start with an example. Consider a second order differential system,

$$\begin{aligned} &m\ddot{z}(t) + b\dot{z}(t) + kz(t) = u(t) \quad . \\ &y(t) = c \cdot z(t) \\ &z(0) = 10, \dot{z}(0) = 0. \end{aligned} \tag{1}$$

The equations could be a model for an analog circuit as shown in figure 2.1(a), where z is the voltage



(a) A circuit implementation.

(b) A mechanical implementation.

FIGURE 2.1. Possible implementations of the system equations.

of node 3, and

$$m = R1 \cdot R2 \cdot C1 \cdot C2 \tag{2}$$

$$k = R1 \cdot C1 + R2 \cdot C2$$

$$b = 1$$

$$c = \frac{R4}{R3 + R4}.$$

Or it could be a lumped-parameter spring-mass mechanical model for the system shown in figure 2.1(b), where z is the position of the mass, m is the mass, k is the spring constant, b is the damping parameter, and $c = 1$.

In general, an ODE-based continuous-time system has the following form:

$$\dot{x} = f(x, u, t) \tag{3}$$

$$y = g(x, u, t) \tag{4}$$

$$x(t_0) = x_0, \tag{5}$$

where, $t \in \Re$, $t \geq t_0$, a real number, is *continuous time*. At any time t, $x \in \Re^n$, an n-tuple of real numbers, is the *state* of the system; $u \in \Re^m$ is the m-dimensional *input* of the system; $y \in \Re^l$ is the l-dimensional *output* of the system; $\dot{x} \in \Re^n$ is the derivative of x with respect to time t, i.e.

$$\dot{x} = \frac{dx}{dt}. \tag{6}$$

Equations (3), (4), and (5) are called the *system dynamics*, the *output map*, and the *initial condition* of the system, respectively.

For example, for the mechanical system above, if we define a vector

$$x(t) = \begin{bmatrix} z(t) \\ \dot{z}(t) \end{bmatrix}, \tag{7}$$

then system (1) can be written in form of (3)-(5), like

$$\dot{x}(t) = \frac{1}{m}\begin{bmatrix} 0 & 1 \\ -k & -b \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 1/m \end{bmatrix} u(t) \tag{8}$$

$$y(t) = \begin{bmatrix} c & 0 \end{bmatrix} x(t)$$

$$x(0) = \begin{bmatrix} 10 \\ 0 \end{bmatrix}.$$

The solution, $x(t)$, of the set of ODE (3)-(5), is a continuous function of time, also called a *waveform*, which satisfies the equation (3) and initial condition (5). The output of the system is then defined as a function of $x(t)$ and $u(t)$, which satisfies (4). The precise solution of a set of ODEs is usually impossible to be found using digital computers. Numerical solutions are approximations of the precise solution. A numerical solution of ODEs are usually done by integrating the right-hand side of (3) on a

discrete set of time points. Using digital computers to simulate continuous-time systems has been studied for more than three decades. One of the most well-known tools is Spice [95]. The CT domain differs from Spice-like continuous-time simulators in two ways — the system specification is somewhat different, and it is designed to interact with other models of computation.

2.1.1 System Specification

There are usually two ways to specify a continuous-time system, the conservation-law model and the signal-flow model [52]. The conservation-law models, like the nodal analysis in circuit simulation [49] and bond graphs [110] in mechanical models, define systems by their physical components, which specify relations of *cross* and *through* variables, and *conservation laws* are used to compile the component relations into global system equations. For example, in circuit simulation, the cross variables are voltages, the through variables are currents, and the conservation laws are Kirchhoff's laws. This model directly reflects the physical components of a system, thus is easy to construct from a potential implementation. The actual mathematical representation of the system is hidden. In signal-flow models, entities in a system are maps that define the mathematical relation between their input and output signals. Entities communicate by passing signals. This kind of models directly reflects the mathematical relations among signals, and is more convenient for specifying systems that do not have an explicit physical implementation yet.

In the CT domain of Ptolemy II, the signal-flow model is chosen as the interaction semantics. The conservation-law semantics may be used within an entity to define its I/O relation. There are four major reasons for this decision:

1. *The signal-flow model is more abstract*. Ptolemy II focuses on system-level design and behavior simulation. It is usually the case that, at this stage of a design, users are working with abstract mathematical models of a system, and the implementation details are unknown or not cared about.

2. *The signal flow model is more flexible and extensible*, in the sense that it is easy to embed components that are designed using other models. For example, a discrete controller can be modeled as a component that internally follows a discrete event model of computation but exposes a continuous-time interface.

3. *The signal flow model is consistent with other models of computation in Ptolemy II*. Most models of computation in Ptolemy use message-passing as the interaction semantics. Choosing the signal-flow model for CT makes it consistent with other domains, so the interaction of heterogeneous systems is easy to study and implement. This also allows domain polymorphic actors to be used in the CT domain.

4. *The signal flow model is compatible with the conservation law model*. For physical systems that are based on conservation laws, it is usually possible to wrap them into an entity in the signal flow model. The inputs of the entity are the excitations, like the current on ideal current sources, and the outputs are the variables that the rest of the system may be interested in.

The signal flow block diagram of the system (3) - (5) is shown in figure 2.2. The system dynamics (3) is built using integrators with feedback. In this figure, u, $\dot{x}$, x, and y, are continuous signals flowing from one block to the next. Notice that this diagram is only conceptual, most models may involve multiple integrators[1]. Time is shared by all components, so it is not considered as an input. At any fixed time t, if the "snapshot" values $x(t)$ and $u(t)$ are given, then $\dot{x}(t)$ and $y(t)$ can be found by evaluating f

1. Ptolemy II does not support vectorization in the CT domain yet.

and *g*, which can be achieved by firing the respective blocks. The "snapshot" of all the signals at t is called the *behavior* of the system at time t.

The signal-flow model for the example system (1) is shown in figure 2.3. For comparison purpose, the conservation-law model (modified nodal analysis) of the system shown in figure 2.1(a) is shown in (9).

$$\begin{bmatrix} \frac{1}{R1} & -\frac{1}{R1} & 0 & 0 & -1 \\ -\frac{1}{R1} & \frac{1}{R1}+\frac{1}{R2}+C1\frac{d}{dt} & -\frac{1}{R2} & 0 & 0 \\ 0 & -\frac{1}{R2} & \frac{1}{R2}+\frac{1}{R3}+C2\frac{d}{dt} & -\frac{1}{R3} & 0 \\ 0 & 0 & -\frac{1}{R3} & \frac{1}{R3}+\frac{1}{R4} & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ y \\ I_1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ u \end{bmatrix} \tag{9}$$

By doing some math, we can see that (9) and (8) are in fact equivalent. Equation (9) can be easily assembled from the circuit, but it is more complicated than (8). Notice that in (9) d/dt is the derivative operator, which is replaced by an integration algorithm at each time step, and the system equations reduce to a set of algebraic equations. Spice software is known to have a very good simulation engine for models in form of (9).

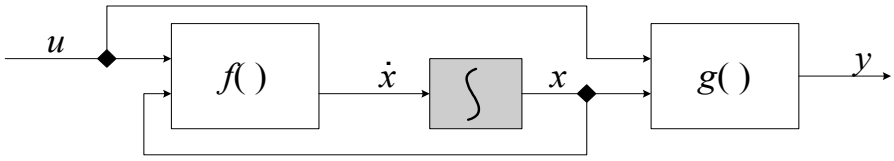


FIGURE 2.2. A conceptual block diagram for continuous time systems.

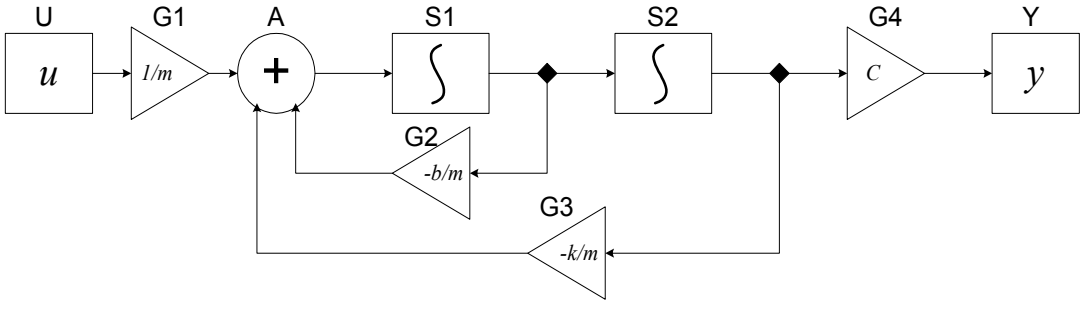


FIGURE 2.3. The block diagram for the example system.

2.1.2 Time

One distinct characterization of the CT model is the continuity of time. This implies that a continuous-time system have a behavior at any time instance. The simulation engine of the CT model should be able to compute the behavior of the system at any time point, although it may march discretely in time. In order to achieve an accurate simulation, time should be carefully discretized. The discretization of time, which appears as integration step sizes, may be determined by time points of interest (e.g. discontinuities), by the numerical error of integration, and by the convergence in solving algebraic equations.

Time is also global, which means that all components in the system share the same notion of time.

2.2 Solving ODEs numerically

We outline some basic terminologies on numerical ODE solving techniques that are used in this chapter. This is not a summary of numerical ODE solving theory. For a detailed treatment for ODEs and their numerical solutions, please refer to books on numerical solutions for ODEs, e.g. [35].

Not all ODEs have a solution, and some ODEs have more than one solution. In such situations, we say that the solution is not well defined. This is usually a result of errors in the system modeling. We restrict our discussion to systems that have unique solutions. Theorem 1 in Appendix A states the conditions for the existence and uniqueness of solutions of ODEs. Roughly speaking, we denote by D a set in $\Re$ which contains at most a finite number of points per unit interval, and let u be piecewise-continuous on $\Re - D$. Then, for any fixed $u(t)$, if f is also piecewise-continuous on $\Re - D$, and f satisfies the Lipschitz condition (see e.g. [35]), then the ODE (3) with the initial condition (5) has a unique solution. The solution is called the *state trajectory* of the system. The key of simulating a continuous-time system numerically is to find an accurate numerical approximation of the state trajectory.

2.2.1 Basic Notations

Usually, only the solution on a finite time interval $[t_0,t_f]$ is needed. A simulation of the system is performed on discrete time points in this interval. We denote by

$$Tc = \{t_0, t_1, t_2, \ldots t_n, \ldots t_f\}, Tc \subset [t_0, t_f], \tag{10}$$

where

$$t_0 < t_1 < t_2 < \ldots < t_n < \ldots < t_f, \tag{11}$$

the set of the discrete time points of interest. To explicitly illustrate the discretization of time and the difference between the precise solution and the numerical solution, we use the following notation in the rest of the chapter:

- t_n : the n-th time point, to explicitly show the discretization of time. However, we write t, if the index n is not important.
- $x[t_i, t_j]$: the *precise* (continuous) state trajectory from time t_i to t_j;
- $x(t_n)$: the *precise* solution of (3) at time t_n;
- x_{t_n} : the *numerical* solution of (3) at time t_n;
- $h_n = t_n - t_{n-1}$: step size of numerical integration. We also write h if the index n in the sequence

is not important. For accuracy reason, h may not be uniform.

- $\|x(t_n) - x_{t_n}\|$: the 2-normed difference between the precise solution and the numerical solution at step *n* is called the (*global*) *error* at step *n*; the difference, when we assume $x_{t_0} \ldots x_{t_{n-1}}$ are precise, is called the *local error* at step *n*. Local errors are usually easy to estimate and the estimation can be used for controlling the accuracy of numerical solutions.

A general way of numerically simulating a continuous-time system is to compute the state and the output of the system in an increasing order of t_n. Such algorithms are called the *time-marching* algorithms, and, in this chapter, we only consider these algorithms. There are variety of time marching algorithms that differ on how x_{t_n} is computed given $x_{t_0} \ldots x_{t_{n-1}}$. The choice of algorithms is application dependent, and usually reflects the speed, accuracy, and numerical stability trade-offs.

2.2.2 Fixed-Point Behavior

Numerical ODE solving algorithms approximate the derivative operator in (3) using the history and the current knowledge on the state trajectory. That is, at time t_n, the derivative of x is approximated by a function of $x_{t_0}, \ldots, x_{t_{n-1}}, x_{t_n}$, i.e.

$$\dot{x}_{t_n} = p(x_{t_0}, \ldots, x_{t_{n-1}}, x_{t_n}) . \tag{12}$$

Plugging (3) in this, we get

$$p(x_{t_0} \ldots x_{t_{n-1}}, x_{t_n}) = f(x_{t_n}, u(t_n), t_n) \tag{13}$$

Depending on whether x_{t_n} explicitly appears in (13), the algorithms are called *explicit integration algorithms* or *implicit integration algorithms*. That is, we end up solving a set of algebraic equations in one of the two forms:

$$x_{t_n} = F_E(x_{t_0}, \ldots, x_{t_{n-1}}) \tag{14}$$

or

$$F_I(x_{t_0}, \ldots, x_{t_n}) = 0 , \tag{15}$$

where F_E and F_I are derived from the time t_n, the input $u(t_n)$, the function *f*, and the history of x and $\dot{x}$. Solving (14) or (15) at a particular time t_n is called an *iteration* of the CT simulation at t_n.

Equation (14) can be solved simply by a function evaluation and an assignment. But the solution of (15) is the *fixed point* of F_I, which may not exist, may not be unique, or may not be able to be found. The *contraction mapping theorem* [17] shows the existence and uniqueness of the fixed-point solution, and provides one way to find it. Given the map F_I that is a local contraction map (generally true for small enough step sizes) and let an initial guess σ_0 be in the contraction radius, then a unique fixed point exists and can be found by iteratively computing:

$$\sigma_1 = F_E(\sigma_0), \sigma_2 = F_E(\sigma_1), \sigma_3 = F_E(\sigma_2), \ldots \tag{16}$$

Solving both (14) and (15) should be thought of as finding the fixed-point behavior of the system at a particular time. This means both functions F_E and F_I should be smooth w.r.t. time, during one iteration of the simulation. This further implies that the topology of the system, all the parameters, and all the internal states that the firing functions depend on should be kept unchanged. We require that

domain polymorphic actors to update internal states only in the `postfire()` method exactly for this reason.

2.2.3 ODE Solvers Implemented

The following solvers has been implemented in the CT domain.

1. Forward Euler solver:

$$\begin{aligned} x_{t_{n+1}} &= x_{t_n} + h_{n+1} \cdot \dot{x}_{t_n} \\ &= x_{t_n} + h_{n+1} \cdot f(x_{t_n}, u_{t_n}, t_n) \end{aligned} \tag{17}$$

2. Backward Euler solver:

$$\begin{aligned} x_{t_{n+1}} &= x_{t_n} + h_{n+1} \cdot \dot{x}_{t_{n+1}} \\ &= x_{t_n} + h_{n+1} \cdot f(x_{t_{n+1}}, u_{t_{n+1}}, t_{n+1}) \end{aligned} \tag{18}$$

3. 2(3)-order Explicit Runge-Kutta solver

$$\begin{aligned} K_0 &= h_{n+1} \cdot f(x_{t_n}, u_{t_n}, t_n) \\ K_1 &= h_{n+1} \cdot f(x_{t_n} + K_0/2, u_{t_n + h_{n+1}/2}, t_n + h_{n+1}/2) \\ K_2 &= h_{n+1} \cdot f(x_{t_n} + 3K_1/4, u_{t_n + 3h_{n+1}/4}, t_n + 3h_{n+1}/4) \\ \tilde{x}_{t_{n+1}} &= x_{t_n} + \frac{2}{9}K_0 + \frac{1}{3}K_1 + \frac{4}{9}K_2 \end{aligned} \tag{19}$$

with error control:

$$\begin{aligned} K_3 &= h_{n+1} \cdot f(\tilde{x}_{t_{n+1}}, u_{t_{n+1}}, t_{n+1}) \\ LTE &= -\frac{5}{72}K_0 + \frac{1}{12}K_1 + \frac{1}{9}K_2 - \frac{1}{8}K_3 \end{aligned} \tag{20}$$

if $|LTE| < ErrorTolerance$, $x_{t_{n+1}} = \tilde{x}_{t_{n+1}}$, otherwise, fail. If this step is successful, the next integration step size is predicted by:

$$h_{n+2} = h_{n+1} \cdot max(0.5, 0.8 \cdot \sqrt[3]{(ErrorTolerance)/|LTE|}) \tag{21}$$

4. Trapezoidal Rule solver:

$$\begin{aligned} x_{t_{n+1}} &= x_{t_n} + \frac{h_{n+1}}{2}(\dot{x}_{t_n} + \dot{x}_{t_{n+1}}) \\ &= x_{t_n} + \frac{h_{n+1}}{2}(\dot{x}_{t_n} + f(x_{t_{n+1}}, u_{t_{n+1}}, t_{n+1})) \end{aligned} \quad . \tag{22}$$

Among these solvers, 1) and 3) are explicit; 2) and 4) are implicit. Also, 1) and 2) do not perform step size control, so are called fixed-step-size solvers; 3) and 4) change step sizes according to error estimation, so are called variable-step-size solvers. Variable-step-size solvers adapt the step sizes according to changes of the system flow, thus are “smarter” than fixed-step-size solvers.

2.2.4 Discontinuity

The existence and uniqueness of the solution of an ODE (Theorem 1 in Appendix A) allows the right-hand side of (3) to be discontinuous at a countable number of discrete points *D*, which are called the *breakpoints* (also called the *discontinuous points* in some literature). These breakpoints may be caused by the discontinuity of input signal *u*, or by the intrinsic flow of *f*. In theory, the solutions at these points are not well defined. But the left and right limits are. So, instead of solving the ODE at those points, we would actually try to find the left and right limits.

One impact of breakpoints on ODE solvers is that history solutions are useless when approximating the derivative of *x* after the breakpoints. The solver should resolve the new initial conditions and start the solving process as if it is at a starting point. So, the discretization of time should step exactly on breakpoints for the left limit, and start at the breakpoint again after finding the right limit.

A breakpoint may be known beforehand, in which case it is called a *predictable breakpoint*. For example, a square wave source actor knows its next flip time. This information can be used to control the discretization of time. A breakpoint can also be *unpredictable*, which means it is unknown until the time it occurs. For example, an actor that varies its functionality when the input signal crosses a threshold can only report a "missed" breakpoint after an integration step is finished. How to handle breakpoints correctly is a big challenge for integrating continuous-time models with discrete models like DE and FSM.

2.2.5 Breakpoint ODE Solvers

Breakpoints in the CT domain are handled by adjusting integration steps. We use a table to handle predictable breakpoints, and use the step size control mechanism to handle unpredictable breakpoints. The breakpoint handling are transparent to users, and the implementation details (provided in section 2.8.4) are only needed when developing new directors, solvers, or event generators.

Since the history information is useless at breakpoints, special ODE solvers are designed to restart the numerical integration process. In particular, we have implemented the following breakpoint ODE solvers.

1. DerivativeResolver:

   It calculates the derivative of the current state, i.e. $\frac{dx}{dt}$. This is simply done by evaluation the right-hand side of (3). At breakpoints, this solver is used for the first step to generate history information for explicit methods or one step methods.

2. ImpulseBESolver:

$$\tilde{x}_{t_{n+1}} = x_{t_n} + h_{n+1} \cdot \tilde{\dot{x}}_{t_{n+1}} \qquad (23)$$
$$x_{t_n^+} = \tilde{x}_{t_{n+1}} - h_{n+1} \cdot \dot{x}_{t_n^+}$$

The two time points t_n and t_n^+ have the same time value. This solver is used for breakpoints at which a Dirac impulse signal appears.

Notice that none of these solvers advance time. They can only be used at breakpoints.

2.3 Signal Types

The CT domain of Ptolemy II supports continuous time mixed-signal modeling. As a consequence, there could be two types of signals in a CT model: continuous signals and discrete events. Note that for both types of signals, time is continuous. These two types of signals directly affect the behavior of a receiver that contains them. A continuous CTReceiver contains a sample of a continuous signal at the current time. Reading a token from that receiver will not consume the token. A discrete CTReceiver may or may not contain a discrete event. Reading from a discrete CTReceiver with an event will consume the event, so that events are processed exactly once[1]. Reading from an empty discrete CTReceiver is not allowed.

Note that some actors can be used to compute on both continuous and discrete signals. For example, an adder can add two continuous signals, as well as two sets of discrete events. Whether a particular link among actors is continuous or discrete is resolved by a *signal type system*. The signal type system understands signal types on specific actors (indicated by the interfaces they implement or the parameters specified on their ports), and try to resolve signal types on the ports of domain polymorphic actors.

The signal type system in the CT domain works on a simple lattice of signal types, shown in Figure 2.4. A type lower in the lattice is more specific than a type higher in the lattice. A CT model is *well-defined* and executable, if and only if all ports are resolved to either CONTINUOUS or DISCRETE. Some actors have their signal types fixed. For example, an `Integrator` has a CONTINUOUS input and a CONTINUOUS output; a `PeriodicSampler` has a CONTINUOUS input and a DISCRETE output; a `TriggeredSampler` has one CONTINUOUS input (the input), one DISCRETE input (the trigger), and a DISCRETE output; and a `ZeroOrderHold` has a DISCRETE input and a CONTINUOUS output. For domain polymorphic actors that implement the `SequenceActor` interface, i.e. they operate solely on sequences of tokens, their inputs and outputs are treated as DISCRETE. For other domain polymorphic actors that can operate on both continuous and discrete signals, the signal type on their ports are initially UNRESOLVED. The signal type system will resolve and check signal types of ports according to the following two rules:

- If a port *p* is connected to another port *q* with a more specific type, then the type of *p* is resolved to that of the port *q*. If *p* is CONTINUOUS but *q* is DISCRETE, then both of them are resolved to

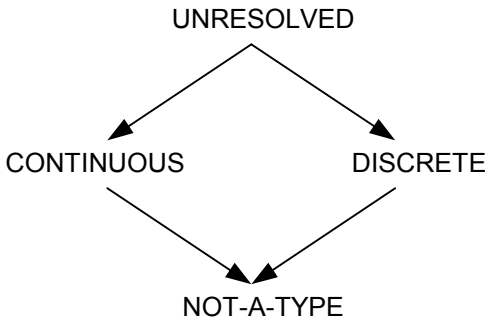


FIGURE 2.4. A signal type lattice.

1. This distinction of receivers is also called state and event semantics in some literatures [57].

NOT-A-TYPE.

- Unless otherwise specified, the types of the input ports and output ports of an actor are the same.

At the end of the signal-type resolution, if any port is of type UNRESOLVED or NOT-A-TYPE, then the topology of the system is illegal, and the execution is denied.

The signal type of a port can also be forced by adding an parameter "signalType" to the port. The signal type system will recognize this parameter and resolve other types accordingly. To add this parameter, right click on the port, select Configure, then add a parameter with the name signalType and the value of a string of either "CONTINUOUS" or "DISCRETE", noting the quotation marks.

Signal types may be more trickier at the boundaries of composite actors than within a CT model. Because of the information hiding, it may not be obvious which port of another level of hierarchy is continuous and which port is discrete. In the CT domain, we follow these rules to resolve signal types for composite ports:

- A `TypedCompositeActor` within a CT model is always treated as entirely discrete. Within a CT model, for any opaque composite actor that may contain continuous dynamics at a deeper level, use the `CTCompositeActor` (listed in the actor library as "continuous time composite actor" in domain specific actors) or the modal model composite actor.
- For a `CTCompositeActor` or a modal model within a CT model, all its ports are treated as continuous by default. To allow a discrete event going through the composite actor boundary, manually set the signal type of that port by adding the signalType parameter.
- For a `TypedCompositeActor` *containing* a CT model, all the ports of the `TypedCompositeActor` are treated as discrete, and the CT director to use is the CTMixedSignalDirector (listed as CTDirector in the vergil director library).
- For a `CTCompositeActor` or a modal model *containing* a CT model, all the signal types of the ports of the container are treated as continuous, and can be set by adding the signalType parameter. The CTDirector to use in this situation is the CTEmbeddedDirector.

2.4 CT Actors

A CT system can be built up using actors in the ptolemy.domains.ct.lib package and domain polymorphic actors that have continuous behaviors (i.e. all actors that do not implement the SequenceActor interface). The key actor in CT is the integrator. It serves the unique role of wiring up ODEs. Other actors in a CT system are usually stateless. A general understanding is that, in a pure continuous-time model, all the information — the state of the system— is stored in the integrators.

2.4.1 CT Actor Interfaces

In order to schedule the execution of actors in a CT model and to support the interaction between CT and other domains (which are usually discrete), we provide the following interfaces.

- **CTDynamicActor**. Dynamic actors are actors that contains continuous dynamics in their I/O path. An integrator is a dynamic actor, and so are all actors that have integration relations from their inputs to their outputs.
- **CTEventGenerator**. *Event generators* are actors that convert continuous time input signals to discrete output signals.
- **CTStatefulActor**. Stateful actors are actors that have internal states. The reason to classify this kind of actor is to support rollback, which may happen when a CT model is embedded in a discrete

event model.

- **CTStepSizeControlActor**. Step size control actors influence the integration step size by telling the director whether the current step is accurate. The accuracy is in the sense of both tolerable numerical errors and absence of unpredictable breakpoints. It may also provide information about refining a step size for an inaccurate step and suggesting the next step size for an accurate step.
- **CTWaveformGenerator**. *Waveform generators* are actors that convert discrete input signals to continuous-time output signals.

Strictly speaking, event generators and waveform generators do not belong to any domain, but the CT domain is design to handle them intrinsically. When building systems, CT parts can always provide discrete interface to other domains.

Neither a loop of dynamic actors nor a loop of non-dynamic actors are allowed in a CT model. They introduce problems about the order that actors be executed. A loop of dynamic actors can be easily broken by a Scale actor with scale 1. A loop of non-dynamic actors builds an algebraic equation. The CT domain does not support modeling algebraic equations, yet.

2.4.2 Actor Library

CTPeriodicalSampler. This event generator periodically samples the input signal and generates events with the value of the input signal at these time points. The sampling rate is given by the *samplePeriod* parameter, which has default value 0.1. The sampling time points, which are known beforehand, are examples of predictable breakpoints.

CTTriggeredSampler. This actor samples the continuous input signal when there is a discrete event present at the "trigger" input.

ContinuousTransferFunction. A transfer function in the continuous time domain. This actor implements a transfer function where the single input (u) and single output (y) can be expressed in (Laplace) transfer function form as the following equation:

$$\frac{Y(s)}{U(s)} = \frac{b_1 s^{m-1} + b_2 s^{m-2} + \ldots + b_m}{a_1 s^{n-1} + a_2 s^{n-2} + \ldots + a_n} \tag{24}$$

where m and n are the number of numerator and denominator coefficients, respectively. This actors has two parameters – *numerator* and *denominator* – containing the coefficients of the numerator and denominator in descending powers of s. The parameters are double arrays. The order of the denominator (n) must be greater than or equal to the order of the numerator (m).

DifferentialSystem. The differential system model implements a system whose behavior is defined by:

$$\begin{aligned} \dot{x} &= f(x, u, t) \\ y &= g(x, u, t) \\ x(t_0) &= x_0 \end{aligned} \tag{25}$$

where x is the state vector, u is the input vector, and y is the output vector, t is the time. Users must give the name of the variables by filling in the parameter and add ports with proper names. The actor, upon creation, has no inputs and no outputs. After creating proper ports, their names can be used in the

expressions of state equations and output equations. The name of the state variables are manually added by filling in the *stateVariableNames* parameter.

The state equations and output maps must be manually created by users as parameters. If there are *n* state variables $x_1 \ldots x_n$ then users need to create *n* additional parameters, one for each state equation. And the parameters must be named as *x1_dot*, ..., *xn_dot*, respectively. Similarly, if the output ports have names $y_1 \ldots y_r$, then users must create additional *r* parameters for output maps. These parameters should be named y_1, ..., y_r, respectively.

Integrator: The integrator for continuous-time simulation. An integrator has one input port and one output port. Conceptually, the input is the derivative of the output, and an ordinary differential equation is modeled as an integrator with feedback.

An integrator is a dynamic, step-size-control, and stateful actor. To help resolve new states from previous states, a set of variables are used:

- *state and its derivative*: These are the new state and its derivative at a time point, which have been confirmed by all the step size control actors.
- *tentative state and tentative derivative*: These are the state and derivative which have not been confirmed. It is a starting point for other actors to estimate the accuracy of this integration step.
- *history*: The previous states and derivatives. An integrator remembers the history states and their derivatives for the past several steps. The history is used by multistep methods.

An integrator has one parameter: *initialState*. At the initialization stage of the simulation, the state of the integrator is set to the initial state. Changes of *initialState* will be ignored after the simulation starts, unless the `initialize()` method of the integrator is called again. The default value of this parameter is 0.0. An integrator can possibly have several auxiliary variables. These auxiliary variables are used by ODE solvers to store intermediate states for individual integrators.

LinearStateSpace. The State-Space model implements a system whose behavior is defined by:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \\ x(t_0) &= x_0 \end{aligned} \tag{26}$$

where *x* is the state vector, *u* is the input vector, and *y* is the output vector. The matrix coefficients must have the following characteristics:

- A must be an *n*-by-*n* matrix, where n is the number of states.
- B must be an *n*-by-*m* matrix, where m is the number of inputs.
- C must be an *r*-by-*n* matrix, where r is the number of outputs.
- D must be an *r*-by-*m* matrix.

The actor accepts *m* inputs and generates *r* outputs through a multiple input port and a multiple output port. The widths of the ports must match the number of rows and columns in corresponding matrices, otherwise, an exception will be thrown.

ZeroCrossingDetector. This is an event generator that monitors the signal coming in from an input port – trigger. If the trigger is zero, then output the token from the input port. Otherwise, there is no output. This actor controls the integration step size to accurately resolve the time that the zero crossing

happens. It has a parameter, *errorTolerance*, which controls how accurately the zero crossing is determined.

ZeroOrderHold. This is a waveform generator that converts discrete events into continuous signals. This actor acts as a zero-order hold. It consumes the token when the `consumeCurrentEvent()` is called. This value will be held and emitted every time it is fired, until the next time `consumeCurrentEvent()` is called. This actor has one single input port, one single output port, and no parameters.

ThresholdMonitor. This actor controls the integration steps so that the given threshold (on the input) is not crossed in one step. This actor has one input port and one output port. It has two parameters *thresholdWidth* and *thresholdCenter*, which have default value 1e-2 and 0, respectively. If the input is within the range defined by the threshold center and threshold width, then a true token is emitted from the output.

2.4.3 Domain Polymorphic Actors

Not all domain polymorphic actors can be used in the CT domain. Whether an actor can be used depends on how the internal states of the actor evolve when executing.

- **Stateless actors**: All stateless actors can be used in CT. In fact, most CT systems are built by integrators and stateless actors.
- **Timed actors**: Timed actors change their states according to the notion of time in the model. All actors that implement the TimedActor interface can be used in CT, as long as they do not also implement SequenceActor. Timed actors that can be used in CT include plotters that are designed to plot timed signals.
- **Sequence actors**: Sequence actors change their states according to the number of input tokens received by the actor and the number of times that the actor is postfired. Since CT is a time driven model, rather than a data driven model, the number of received tokens and the number of postfires do not have a significant semantic meaning. So, none of the sequence actors can be used in the CT domain. For example, the Ramp actor in Ptolemy II changes its state –– the next token to emit –– corresponding to the number of times that the actor is postfired. In CT, the number of times that the actor is postfired depends on the discretization of time, which further depend on the choice of ODE solvers and setting of parameters. As a result, the slope of the ramp may not be a constant, and this may lead to very counterintuitive models. The same functionality is replaced by a CurrentTime actor and a Scale actor. If sequence behaviors are indeed required, event generators and waveform generators may be helpful to convert continuous and discrete signals.

2.5 CT Directors

There are three CT directors –– CTMultiSolverDirector, CTMixedSignalDirector, and CTEmbeddedDirector. The first one can only serve as a top-level director, a CTMixedSignalDirector can be used both at the top-level or inside a composite actor, and a CTEmbeddedDirector can only be contained in a CTCompositeActor. In terms of mixing models of computation, all the directors can execute composite actors that implement other models of computation, as long as the composite actors are properly connected (see section 2.6). Only CTMixedSignalDirector and CTEmbeddedDirector can be contained by other domains. The outside domain of a composite actor with CTMixedSignalDirector can be any discrete domain, such as DE, DT, etc. The outside domain of a composite actor with CTEmbeddedDi-

rector must also be CT or FSM, if the outside domain of the FSM model is CT. (See also the HSDirector in the FSM domain.)

2.5.1 ODE Solvers

There are six ODE solvers implemented in the ptolemy.domains.ct.kernel.solver package. Some of them are specific for handling breakpoints. These solvers are ForwardEulerSolver, BackwardEulerSolver, ExplicitRK23Solver, TrapezoidalRuleSolver, DerivativeResolver, and ImpulseBESolver. They implement the ODE solving algorithms in section 2.2.3 and section 2.2.5, respectively.

2.5.2 CT Director Parameters

The CTDirector base class maintains a set of parameters which controls the execution. These parameters, shared by all CT directors, are listed in Table 9 on page 34. Individual directors may have their own (additional) parameters, which will be discussed in the appropriate sections.

Table 9: CTDirector Parameters

Name	Description	Type	Default Value
errorTolerance	The upper bound of local errors. Actors that perform integration error control (usually integrators in variable step size ODE solving methods) will compare the estimated local error to this value. If the local error estimation is greater than this value, then the integration step is considered inaccurate, and should be restarted with a smaller step sizes.	double	1e-4
initStepSize	This is the step size that users specify as the desired step size. For fixed step size solvers, this step size will be used in all non-breakpoint steps. For variable step size solvers, this is only a suggestion.	double	0.1
maxIterations	This is used to avoid the infinite loops in (implicit) fixed-point iterations. If the number of fixed-point iterations exceeds this value, but the fixed point is still not found, then the fixed-point procedure is considered failed. The step size will be reduced by half and the integration step will be restarted.	int	20
maxStepSize	The maximum step size used in a simulation. This is the upper bound for adjusting step sizes in variable step-size methods. This value can be used to avoid sparse time points when the system dynamic is simple.	double	1.0
minStepSize	The minimum step size used in a simulation. This is the lower bound for adjusting step sizes. If this step size is used and the errors are still not tolerable, the simulation aborts. This step size is also used for the first step after breakpoints.	double	1e-5
startTime	The start time of the simulation. This is only applicable when CT is the top level domain. Otherwise, the CT director follows the time of its executive director.	double	0.0
stopTime	The stop time of the simulation. This is only applicable when CT is the top level domain. Otherwise, the CT director follows the time of its executive director.	double	Double.MAX_VALUE
synchronizeToRealTime	Indicate whether the execution of the model is synchronized to real time at best effort.	boolean	false
timeResolution	This controls the comparison of time. Since time in the CT domain is a double precision real number, it is sometimes impossible to reach or step at a specific time point. If two time points are within this resolution, then they are considered identical.	double	1e-10

Table 9: CTDirector Parameters

Name	Description	Type	Default Value
valueResolution	This is used in (implicit) fixed-point iterations. If in two successive iterations the difference of the states is within this resolution, then the integration step is called converged, and the fixed point is considered reached.	double	1e-6

2.5.3 CTMultiSolverDirector

A CTMultiSolverDirector has two ODE solvers — one for ordinary use and one specifically for breakpoints. Thus, besides the parameters in the CTDirector base class, this class adds two more parameters as shown in Table 10 on page 35.

Table 10: Additional Parameter for CTMultiSolverDirector

Name	Description	Type	Default Value
ODESolver	The fully qualified class name for the ODE solver class.	string	"ptolemy.domains.ct.kernel.solver.ForwardEulerSolver"
breakpointODESolver	The fully qualified class name for the breakpoint ODE solver class.	string	"ptolemy.domains.ct.kernel.solver.DerivativeResolver"

A CTMultiSolverDirector can direct a model that has composite actors implementing other models of computation. One simulation iteration is done in two phases: the continuous phase and the discrete phase. Let the current iteration be *n.* In the continuous phase, the differential equations are integrated from time t_{n-1} to t_n. After that, in the discrete phase, all (discrete) events which happen at t_n are processed. The step size control mechanism will assure that no events will happen between t_{n-1} and t_n.

2.5.4 CTMixedSignalDirector

This director is designed to be the director when a CT subsystem is contained in an event-based system, like DE or DT. As proved in [80], when a CT subsystem is contained in the DE domain, the CT subsystem should run ahead of the global time, and be ready for rollback. This director implements this optimistic execution.

Since the outside domain is event-based, each time the embedded CT subsystem is fired, the input data are events. In order to convert the events to continuous signals, breakpoints have to be introduced. So this director extends CTMultiSolverDirector, which always has two ODE solvers. There is one more parameter used by this director — the *runAheadLength*, as shown in Table 11 on page 35.

Table 11: Additional Parameter for CTMixedSignalDirector

Name	Description	Type	Default Value
runAheadLength	The maximum length of time for the CT subsystem to run ahead of the global time.	double	1.0

When the CT subsystem is fired, the CTMixedSignalDirector will get the current time τ and the next iteration time τ' from the outer domain, and take the $\min(\tau - \tau', l)$ as the fire end time, where l is the value of the parameter *maxRunAheadLength*. The execution lasts as long as the fire end time is

not reached or an output event is not detected.

This director supports rollback; that is when the state of the continuous subsystem is confirmed (by knowing that no events with a time earlier than the CT current time will be present), the state of the system is marked. If an optimistic execution is known to be wrong, the state of the CT subsystem will roll back to the latest marked state.

2.5.5 CTEmbeddedDirector

This director is used when a CT subsystem is embedded in another continuous time system, either directly or through a hierarchy of finite state machines, like in the hybrid system scenario [82]. This director can pass step size control information up to its executive director. To achieve this, the director must be contained in a CTCompositeActor, which implements the CTStepSizeControlActor interface and can pass the step size control information from the inner domain to the outer domain.

This director extends CTMultiSolverDirector, with no additional parameters. A major difference between this director and the CTMixedSignalDirector is that this director does not support rollback. In fact, when a CT subsystem is embedded in a continuous-time environment, rollback is not necessary.

2.6 Interacting with Other Domains

The CT domain can interact with other domains in Ptolemy II. In particular, we consider interaction among the CT domain, the discrete event (DE) domain and the finite state machine (FSM) domain. Following circuit design communities, we call a composition of CT and DE a *mixed-signal model*; following control and computation communities, we call a composition of CT and FSM a *hybrid system model*.

There are two ways to put CT and DE models together, depending on the containment relation. In either case, event generators and waveform generators are used to convert the two types of signals. Figure 2.5 shows a DE component wrapped by an event generator and a waveform generator. From the input/output point of view, it is a continuous time component. Figure 2.6 shows a CT subsystem

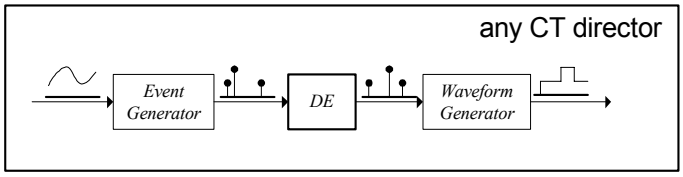


FIGURE 2.5. Embedding a DE component in a CT system.

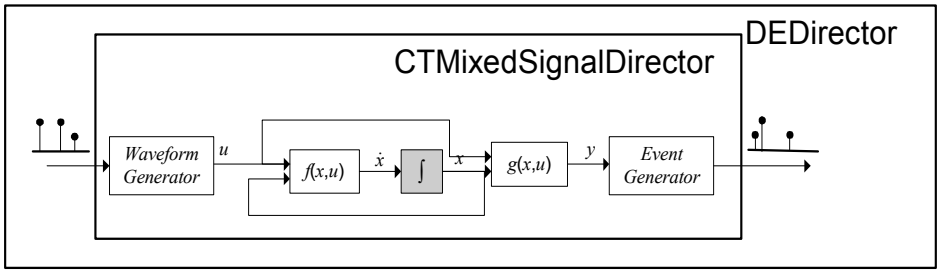


FIGURE 2.6. Embedding a CT component in a DE system.

wrapped by a waveform generator and an event generator. From the input/output point of view, it is a discrete event component. Notice that event generators and waveform generators always stay in the CT domain.

A hierarchical composition of FSM and CT is shown in figure 2.7. A CT component, by adopting the event generation technique, can have both continuous and discrete signals as its output. The FSM can use predicates on these signals, as well as its own input signals, to build trigger conditions. The actions associated with transitions are usually setting parameters in the destination state, including the initial conditions of integrators.

2.7 CT Domain Demos

Here are some demos in the CT domain showing how this domain works and the interaction with other domains.

2.7.1 Lorenz System

The Lorenz System (see, for example, pp. 213-214 in [30]) is a famous nonlinear dynamic system that shows chaotic attractors. The system is given by:

$$\begin{aligned} \dot{x}_1 &= \sigma(x_2 - x_1) \\ \dot{x}_2 &= (\lambda - x_3)x_1 - x_2 \\ \dot{x}_3 &= x_1 \cdot x_2 - b \cdot x_3 \end{aligned} \tag{27}$$

The system is built by integrators and stateless domain polymorphic actors, as shown in figure 2.8.

The result of the state trajectory projecting onto the (x_1, x_2) plane is shown in figure 2.9. The initial conditions of the state variables are all 1.0. The default value of the parameters are: $\sigma = 1, \lambda = 25, b = 2.0$.

2.7.2 Microaccelerometer with Digital Feedback.

Microaccelerometers are MEMS devices that use beams, gaps, and electrostatics to measure acceleration. Beams and anchors, separated by gaps, form parallel plate capacitors. When the device is accelerated in the sensing direction, the displacement of the beams causes a change of the gap size, which further causes a change of the capacitance. By measuring the change of capacitance (using a

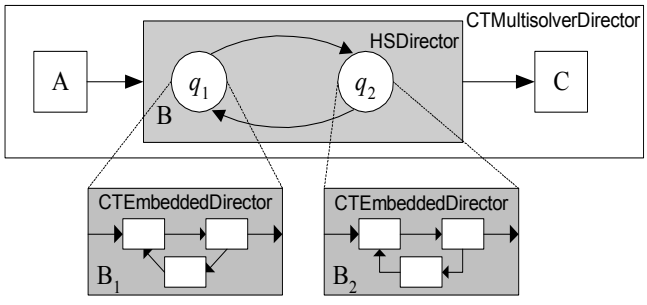


FIGURE 2.7. Hybrid system modeling.

capacitor bridge), the acceleration can be obtained accurately. Feedback can be applied to the beams by charging the capacitors. This feedback can reduce the sensitivity to process variations, eliminate mechanical resonances, and increase sensor bandwidth, selectivity, and dynamic range.

Sigma-delta modulation [20], also called pulse density modulation or a bang-bang control, is a digital feedback technique, which also provides the A/D conversion functionality. Figure 2.10 shows the conceptual diagram of system. The central part of the digital feedback is a one-bit quantizer.

We implemented the system as Mark Alan Lemkin designed [72]. As shown in the figure 2.11, the

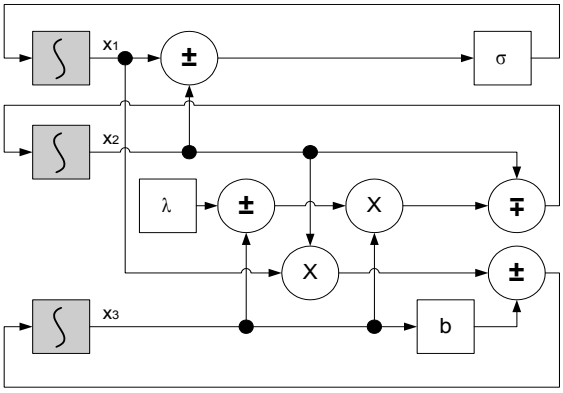


FIGURE 2.8. Block diagram for the Lorenz system.

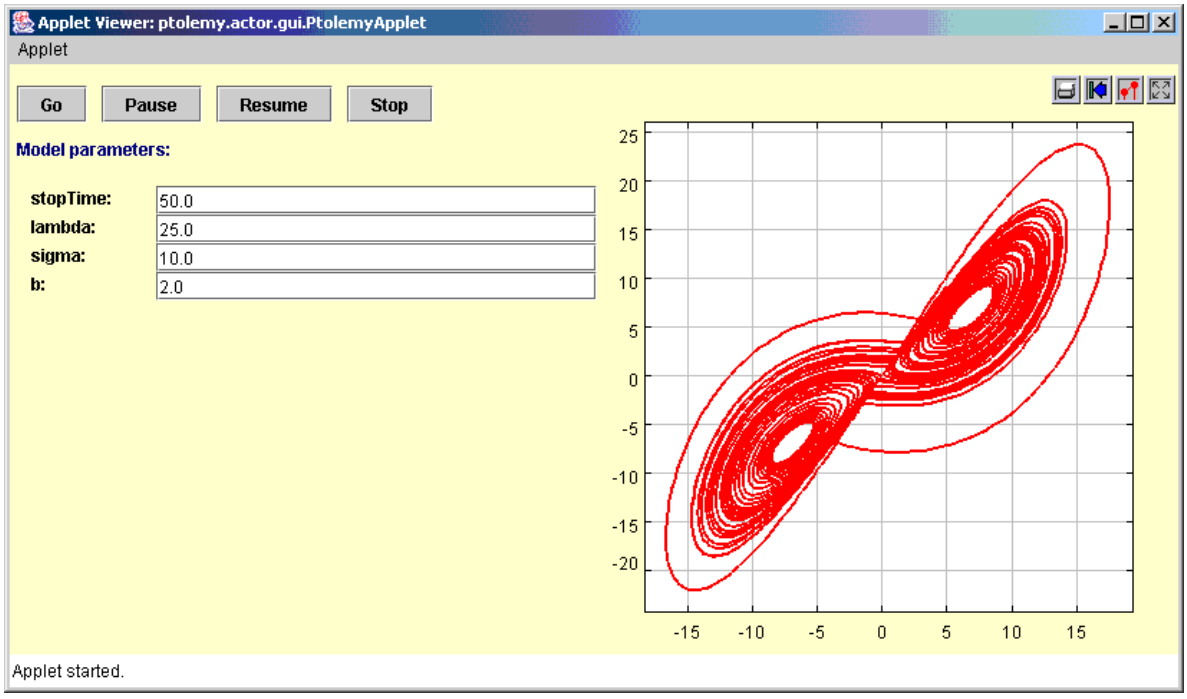


FIGURE 2.9. The simulation result of the Lorenz system.

second order CT subsystem is used to model the beam. The voltage on the beam-gap capacitor is sampled every *T* seconds (much faster than the required output of the digital signal), then filtered by a lead compensator (FIR filter), and fed to an one-bit quantizer. The outputs of the quantizer are converted to force and fed back to the beams. The outputs are also counted and averaged every *NT* seconds to produce the digital output. In our example, the external acceleration is a sine wave.

The execution result of the microaccelerometer system is shown in figure 2.12. The upper plot in the figure plots the continuous signals, where the low frequency (blue) sine wave is the acceleration input, the high frequency waveform (red) is the capacitance measurement, and the squarewave (green) is the zero-order hold of the feedback from the digital part. In the lower plot, the dense events (blue) are the quantized samples of the capacitance measurements, which has value +1 or -1, and the sparse events (red) are the accumulation and average of the previous 64 quantized samples. The sparse events are the digital output, and as expected, they have a sinsoidal shape.

2.7.3 Sticky Point Masses System

This sticky point mass demo shows a simple hybrid system. As shown in figure 2.13, there are two point masses on a frictionless table with two springs attaching them to fixed walls. Given initial positions other than the equilibrium points, the point masses oscillate. The distance between the two walls are close enough that the two point masses may collide. The point masses are sticky, in the way so that when they collide, they will sticky together and become one point mass with two springs attached to it. We also assume that the stickiness decays exponentially after the collision, such that eventually the

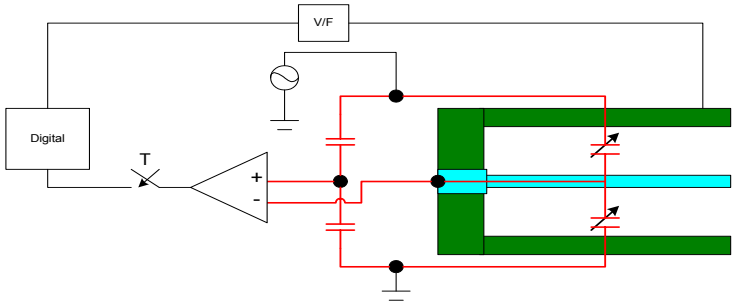


FIGURE 2.10. Micro-accelerator with digital feedback

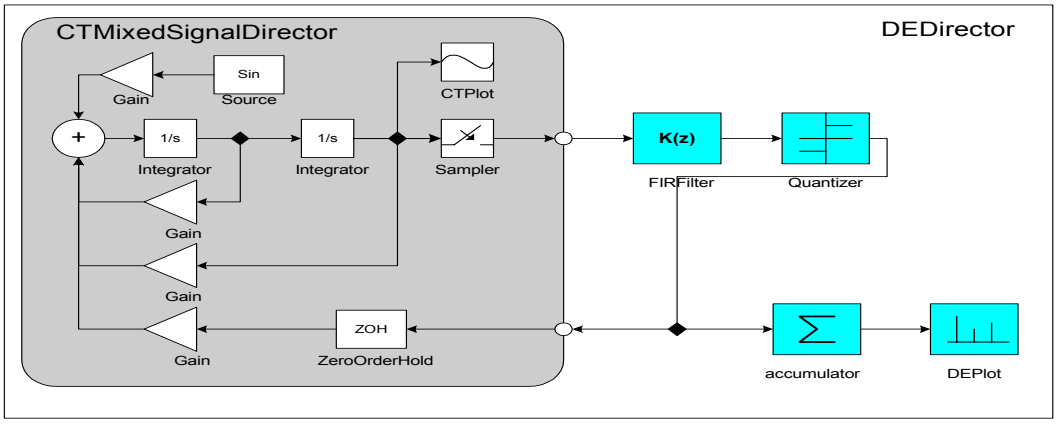


FIGURE 2.11. Block diagram for the micro-accelerator system.

pulling force between the two springs is big enough to pull the point masses apart. This separation gives the two point masses a new set of initial positions, and they oscillate freely until they collide again.

The system model, as shown in figure 2.14, has three levels of hierarchy –– CT, FSM, and CT. The top level is a continuous time model with two actors, a CTCompositeActor that outputs the position of the two point masses, and a plotter that simply plots the trajectories. The composite actor is a finite state machine with two modes, *separated* and *together*.

In the separated state, there are two differential equations modeling two independently oscillating point masses. There is also an event detection mechanism, implemented by subtracting one position from another and comparing the result to zero. If the positions are equal, within a certain accuracy, then the two point masses collide, and a collision event is generated. This event will trigger a transition from the separated state to the together state. And the actions on the transition set the velocity of the stuck point mass based on Law of Conservation of Momentum.

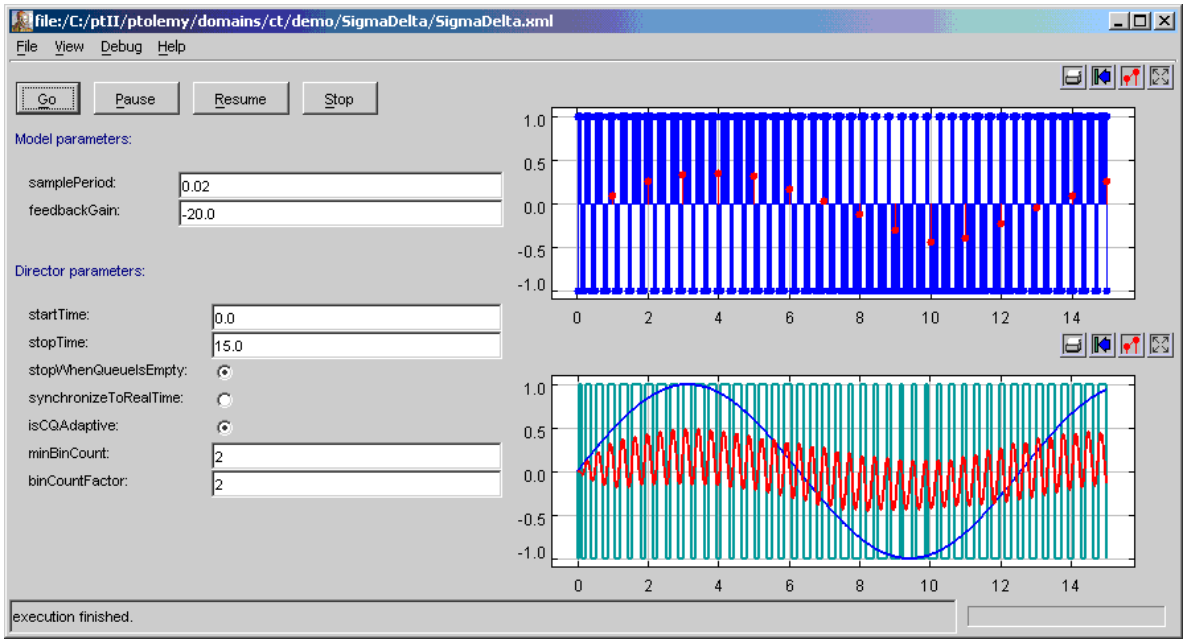


FIGURE 2.12. Execution result of the microaccelerometer system.

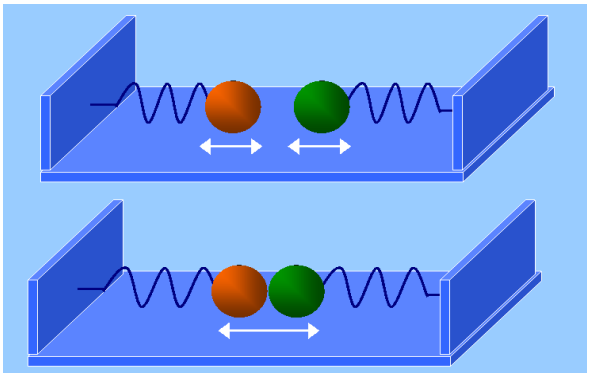


FIGURE 2.13. Sticky point masses system

In the together state, there is one differential equation modeling the stuck point masses, and another first order differential equation modeling the exponentially decaying stickiness. There is another expression computing the pulling force between the two springs. The guard condition from the together state to the separated state compares the pulling force to the stickiness. If the pulling force is bigger than the stickiness, then the transition is taken. The velocities of the two separated point masses equal to their velocities before the separation. The simulation result is shown in figure 2.15, where the position of the two point masses are plotted.

2.8 Implementation

The CT domain consists of the following packages, ct.kernel, ct.kernel.util, ct.kernel.solver, and ct.lib, as shown in figure 2.16.

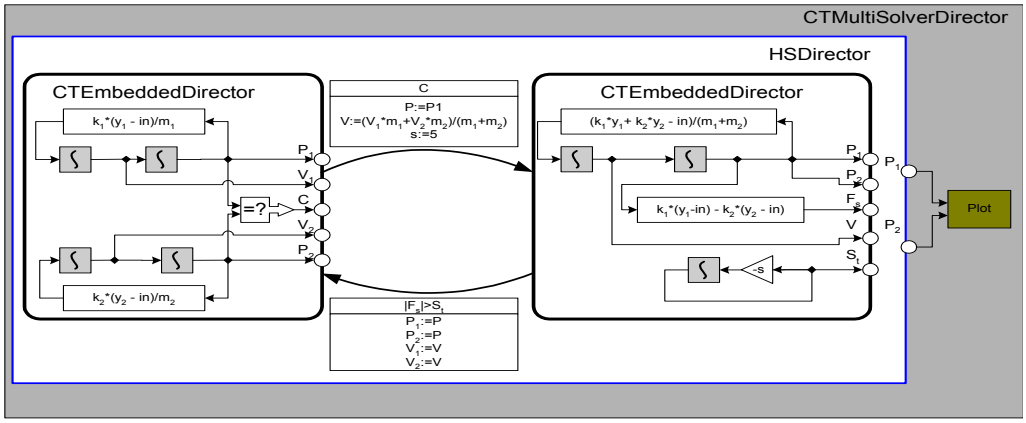


FIGURE 2.14. Modeling sticky point masses.

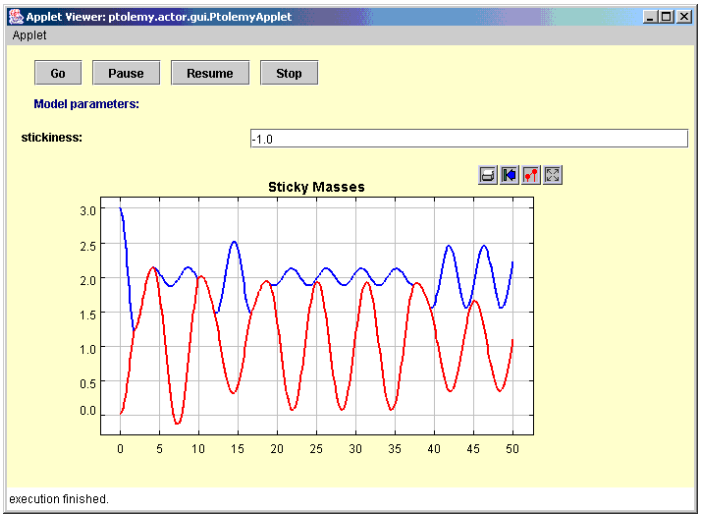


FIGURE 2.15. The simulation result of the sticky point masses system.

2.8.1 ct.kernel.util package

The ct.kernel.util package provides a basic data structure — `TotallyOrderedSet`, which is used to store breakpoints. The UML for this package is shown in figure 2.17. A totally ordered set is a set (i.e. no duplicated elements) in which the elements are totally comparable. This data structure is used to store breakpoints since breakpoints are processed in their chronological order.

2.8.2 ct.kernel package

The ct.kernel package is the key package of the CT domain. It provides interfaces to classify actors, scheduler, director, and a base class for ODE solvers. The interfaces are used by the scheduler to generate schedules. The classes, including the `CTBaseIntegrator` class and the `ODESolver` class, are shown in figure 2.18. Here, we use the delegation and the strategy design patterns [39][34] in the `CTBaseIntegrator` and the `ODESolver` classes to support seamlessly changing ODE solvers without reconstructing integrators. The execution methods of the `CTBaseIntegrator` class are delegated to the `ODESolver` class, and subclasses of `ODESolver` provide the concrete implementations of these methods, depending on the ODE solving algorithms.

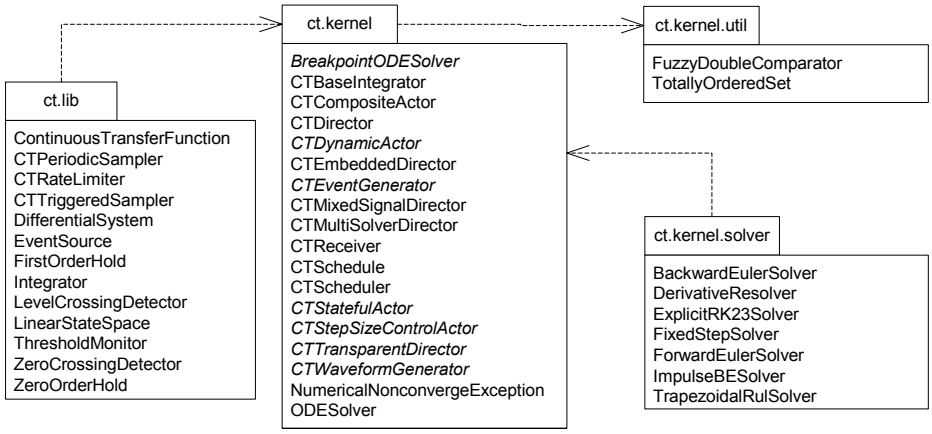


FIGURE 2.16. The packages in the CT domain.

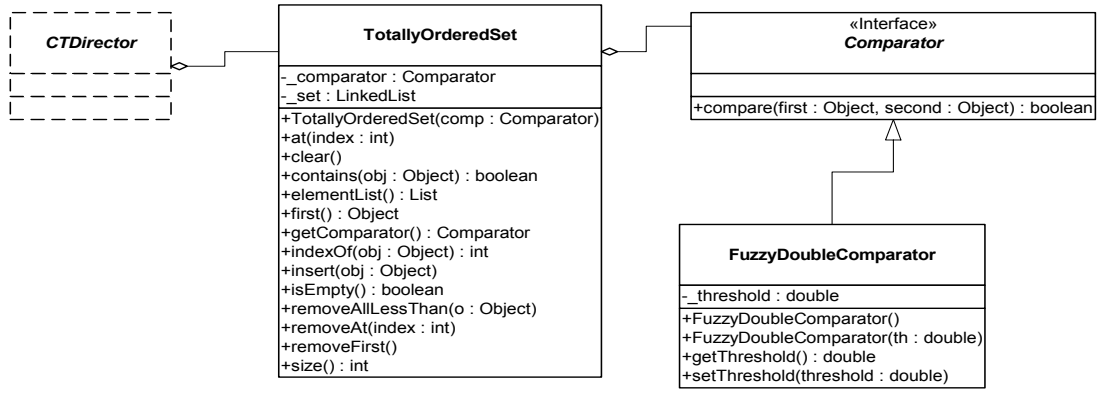


FIGURE 2.17. UML for ct.kernel.util package.

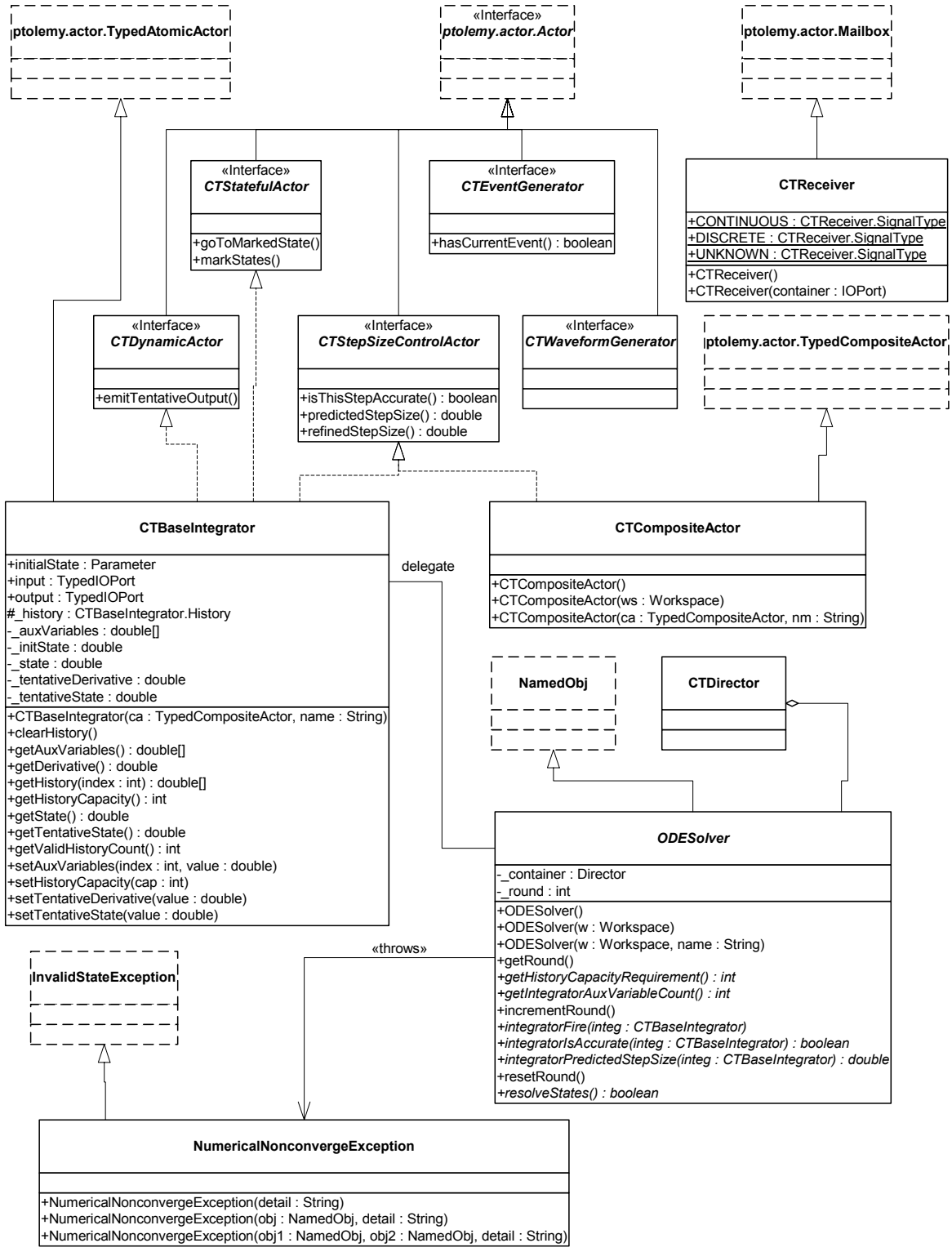


FIGURE 2.18. UML for ct.kernel package, actor related classes.

CT directors implement the semantics of the continuous time execution. As shown in figure 2.19, directors that are used in different scenarios derive from the `CTDirector` base class. The `CTScheduler` class provides schedules for the directors.

The ct.kernel.solver package provides a set of ODE solvers. The classes are shown in figure 2.20. In order for the directors to choose among ODE solvers freely during the execution, the strategy design pattern is used again. A director class talks to the abstract `ODESolver` base class and individual ODE solver classes extend the `ODESolver` to provide concrete strategies.

2.8.3 Scheduling

This section and the following three sections provide technical details and design decisions made in the implementation of the CT domain. These details are only necessary if the readers want to implement new directors or ODE solvers.

In general, simulating a continuous-time system (3)-(5) by a time-marching ODE solver involves the following execution steps:

1. Given the state of the system $x_{t_0} \ldots x_{t_{n-1}}$ at time points $t_0 \ldots t_{n-1}$, if the current integration step size is h, i.e. $t_n = t_{n-1} + h$, compute the new state x_{t_n} using the numerical integration algorithms. During the application of an integration algorithm, each evaluation of the $f(a, b, t)$ function is achieved by the following sequence:

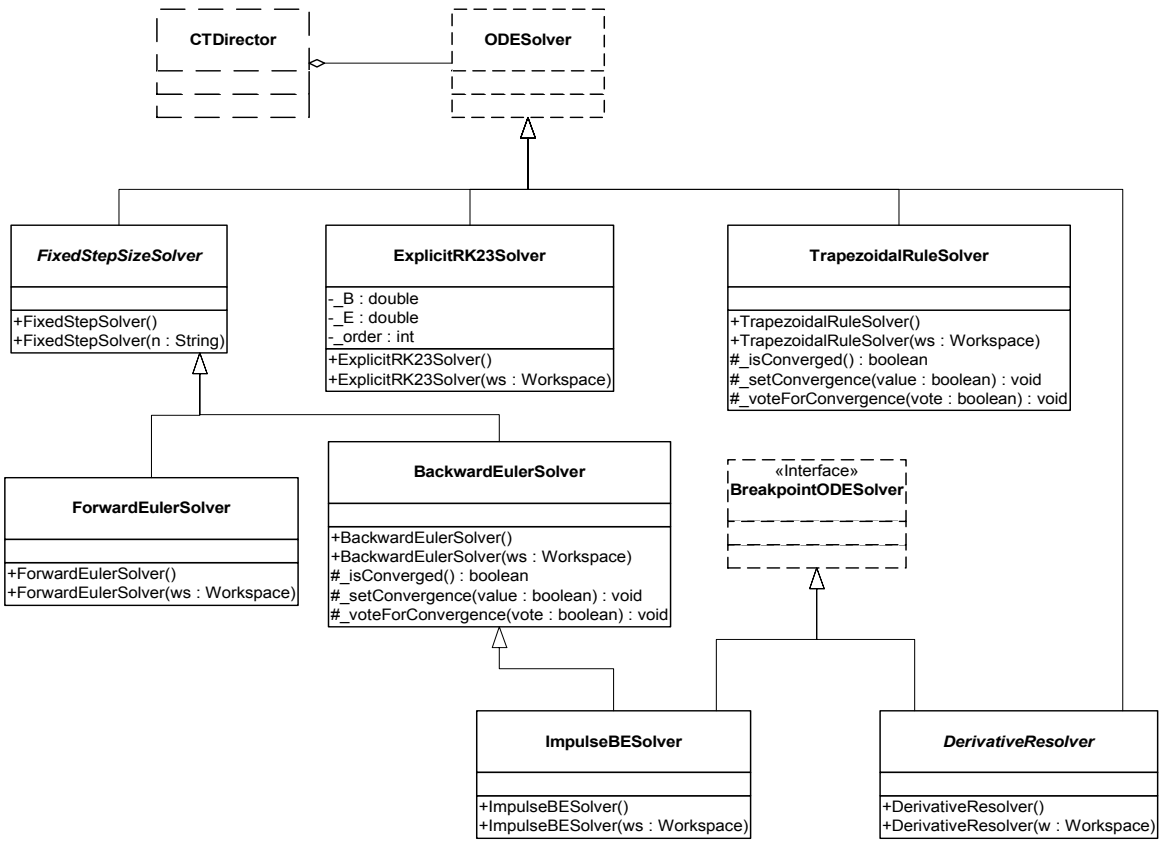


FIGURE 2.20. UML for ct.kernel.solver package.

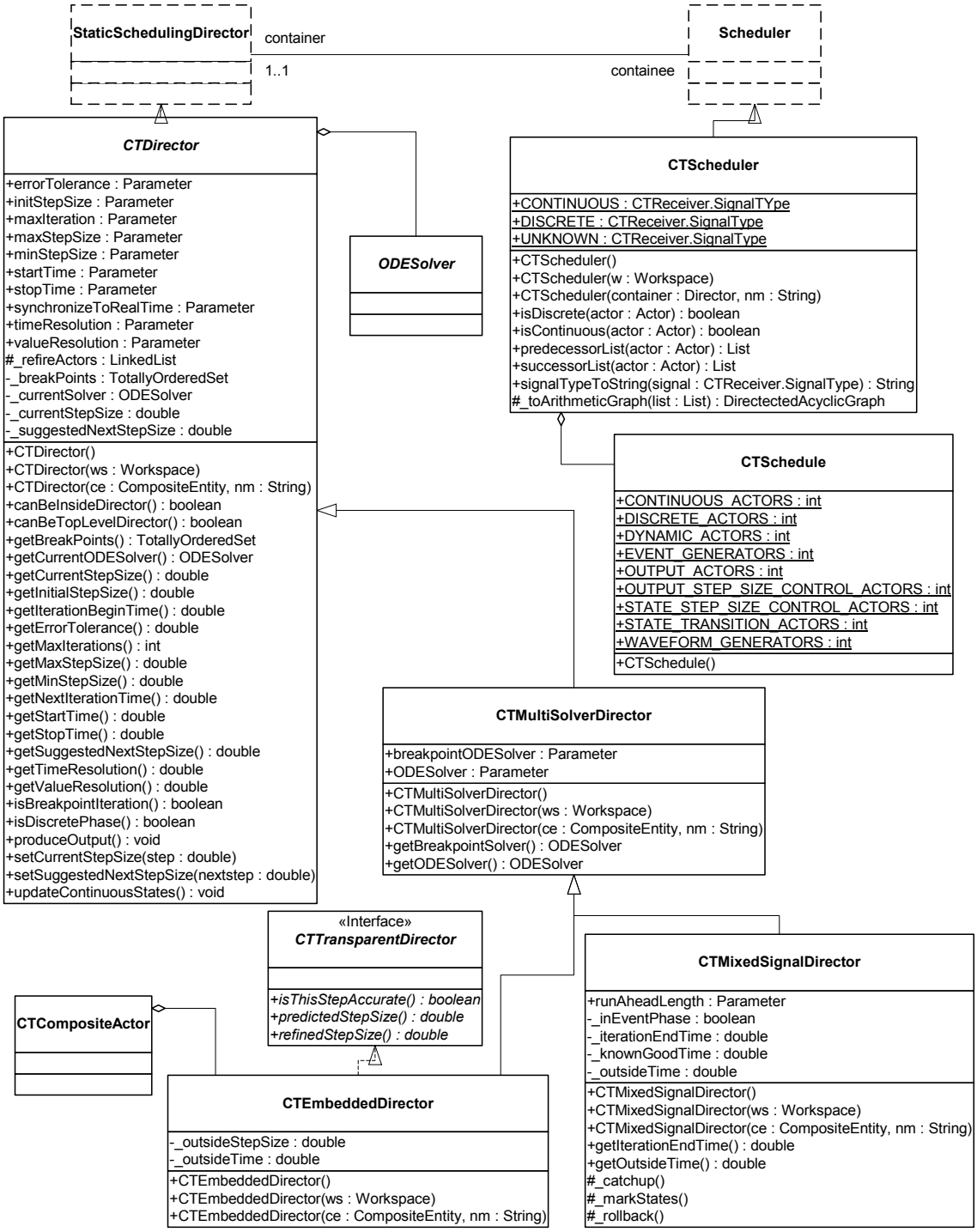


FIGURE 2.19. UML for ct.kernel package, director related classes.

- Integrators emit tokens corresponding to *a*;
- Source actors emit tokens corresponding to *b*;
- The current time is set to *t*;
- The tokens are passed through the topology (in a data-driven way) until they reach the integrators again. The returned tokens are $\dot{x}|_{x=a} = f(a, b, t)$.

2. After the new state x_{t_n} is computed, test whether this step is successful. Local truncation error and unpredictable breakpoints are the issues to be concerned with, since those could lead to an unsuccessful step.

3. If the step is successful, predict the next step size. Otherwise, reduce the step size and try again.

Due to the signal-flow representation of the system, the numerical ODE solving algorithms are implemented as actor firings and token passings under proper scheduling.

The scheduler partitions a CT system into two clusters: the *state transition cluster* and the *output cluster*. In a particular system, these clusters may overlap.

The state transition cluster includes all the actors that are in the signal flow path for evaluating the *f* function in (3). It starts from the source actors and the outputs of the integrators, and ends at the inputs of the integrators. In other words, integrators, and in general dynamic actors, are used to break causality loops in the model. A topological sort of the cluster provides an enumeration of actors in the order of their firings. This enumeration is called the *state transition schedule*. After the integrators produce tokens representing x_t, one iteration of the state transition schedule gives the tokens representing $\dot{x}_t = f(x_t, u(t), t)$ back to the integrators.

The output cluster consists of actors that are involved in the evaluation of the output map *g* in (4). It is also similarly sorted in topological order. The *output schedule* starts from the source actors and the integrators, and ends at the sink actors.

For example, for the system shown in figure 2.3, the state transition schedule is

```
U-G1-G2-G3-A
```

where the order of `G1`, `G2`, and `G3` are interchangeable. The output schedule is

```
G4-Y
```

The event generating schedule is empty.

A special situation that must be taken care of is the firing order of a chain of integrators, as shown in figure 2.21. For the implicit integration algorithms, the order of firings determines two distinct kinds of fixed point iterations. If the integrators are fired in the topological order, namely $x_1 \rightarrow x_2$ in our example, the iteration is called the *Gauss-Seidel iteration*. That is, x_2 always uses the new guess from x_1 in this iteration for its new guess. On the other hand, if they are fired in the reverse topological order, the iteration is called the *Gauss-Jacobi iteration*, where x_2 uses the tentative output from x_1 in the last iteration for its new estimation. The two iterations both have their pros and cons, which are thoroughly discussed in [98]. Gauss-Seidel iteration is considered faster in the speed of convergence than Gauss-Jacobi. For explicit integration algorithms, where the new states x_{t_n} are calculated solely from the history inputs up to $\dot{x}_{t_{n-1}}$, the integrators must be fired in their reverse topological order. For

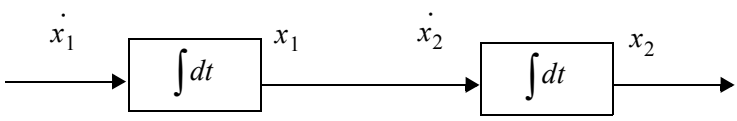


FIGURE 2.21. A chain of integrators.

simplicity, the scheduler of the CT domain, at this time, always returns the reversed topological order of a chain of integrators. This order is considered safe for all integration algorithms.

2.8.4 Controlling Step Sizes

Choosing the right time points to approximate a continuous time system behavior is one of the major tasks of simulation. There are three factors that may impact the choice of the step size.

- *Error control*. For all integration algorithms, the *local error* at time t_n is defined as a vector norm (say, the 2-norm) of the difference between the actual solution $x(t_n)$ and the approximation x_{t_n} calculated by the integration method, given that the last step is accurate. That is, assuming $x_{t_{n-1}} = x(t_{n-1})$ then

$$E_{t_n} = \left\| x_{t_n} - x(t_n) \right\| . \tag{28}$$

  It can be shown that by carefully choosing the parameters in the integration algorithms, the local error is approximately of the p-th order of the step size, where p, an integer closely related to the number of f function evaluations in one integration step, is called the *order* of the integration algorithm, i.e. $E_{t_n} \sim O((t_n - t_{n-1})^p)$. Therefore, in order to achieve an accurate solution, the step size should be chosen to be small. But on the other hand, small step sizes means long simulation time. In general, the choice of step size reflects the trade-off between speed and accuracy of a simulation.
- *Convergence*. The local contraction mapping theorem (Theorem 2 in Appendix A) shows that for implicit ODE solvers, in order to find the fixed point at t_n, the map $F_I(\ )$ in (15) must be a (local) contraction map, and the initial guess must be within an ε ball (the contraction radius) of the solution. It can be shown that $F_I(\ )$ can be made contractive if the step size is small enough. (The choice of the step size is closely related to the Lipschitz constant). So the general approach for resolving the fixed point is that if the iterating function $F_I(\ )$ does not converge at one step size, then reduce the step size by half and try again.
- *Discontinuity.* At discontinuous points, the derivatives of the signals are not continuous, so the integration formula is not applicable. That means the discontinuous points can not be crossed by one integration step. In particular, suppose the current time is t and the intended next time point is $t+h$. If there is a discontinuous point at $t + \delta$, where $\delta < h$, then the next step size should be reduced to $t + \delta$. For a predictable breakpoint, the director can adjust the step size accordingly before starting an integration step. However for an unpredictable breakpoint, which is reported "missed" after an integration step, the director should be able to discard its last step and restart with a smaller step size to locate the actual discontinuous point.

Notice that convergence and accuracy concerns only apply to some ODE solvers. For example, explicit algorithms do not have the convergence problem, and fixed step size algorithms do not have the error control capability. On the other hand, discontinuity control is a generic feature that is independent on the choice of ODE solvers.

2.8.5 Mixed-Signal Execution

DE inside CT.

Since time advances monotonically in CT and events are generated chronologically, the DE component receives input events monotonically in time. In addition, a composition of causal DE components is causal [66], so the time stamps of the output events from a DE component are always greater

than or equal to the global time. From the view point of the CT system, the events produced by a DE component are predictable breakpoints.

Note that in the CT model, finding the numerical solution of the ODE at a particular time is semantically an instantaneous behavior. During this process, the behavior of all components, including those implemented in a DE model, should keep unchanged. This implies that the DE components should not be executed during one integration step of CT, but only between two successive CT integration steps.

CT inside DE.

When a CT component is contained in a DE system, the CT component is required to be causal, like all other components in the DE system. Let the CT component have local time t, when it receives an input event with time stamp τ. Since time is continuous in the CT model, it will execute from its local time t, and may generate events at any time greater or equal to t. Thus we need

$$t \geq \tau \tag{29}$$

to ensure causality. This means that the local time of the CT component should always be greater than or equal to the global time whenever it is executed.

This ahead-of-time execution implies that the CT component should be able to remember its past states and be ready to rollback if the input event time is smaller than its current local time. The state it needs to remember is the state of the component after it has processed an input event. Consequently, the CT component should not emit detected events to the outside DE system before the global time reaches the event time. Instead, it should send a pure event to the DE system at the event time, and wait until it is safe to emit it.

2.8.6 Hybrid System Execution

Although FSM is an untimed model, its composition with a timed model requires it to transfer the notion of time from its external model to its internal model. During continuous evolution, the system is simulated as a CT system where the FSM is replaced by the continuous component refining the current FSM state. After each time point of CT simulation, the triggers on the transitions starting from the current FSM state are evaluated. If a trigger is enabled, the FSM makes the corresponding transition. The continuous dynamics of the destination state is initialized by the actions on the transition. The simulation continues with the transition time treated as a breakpoint.

Appendix A: Brief Mathematical Background

Theorem 1. [Existence and uniqueness of the solution of an ODE] Consider the initial value ODE problem

$$\begin{aligned} \dot{x} &= f(x, t) \quad . \\ x(t_0) &= x_0 \end{aligned} \tag{30}$$

If f satisfies the conditions:

1. [*Continuity Condition*] Let D be the set of possible discontinuity points; it may be empty. For each fixed $x \in \Re^n$ and $u \in \Re^m$, the function $f: \Re \setminus \mathrm{D} \to \Re^n$ in (30) is continuous. And $\forall \tau \in D$, the left-hand and right-hand limit $f(x, u, \tau^-)$ and $f(x, u, \tau^+)$ are finite.
2. [*Lipschitz Condition*] There is a piecewise continuous bounded function $k: \Re \to \Re^+$, where $\Re^+$ is the set of non-negative real numbers, such that $\forall t \in \Re$, $\forall \zeta, \xi \in \Re^n$, $\forall u \in \Re^m$

$$\| f(\xi, u, t) - f(\zeta, u, t) \| \le k(t) \| \xi - \zeta \| . \tag{31}$$

Then, for each initial condition $(t_0, x_0) \subseteq \Re \times \Re^n$ there exists a *unique* continuous function $\psi: \Re \to \Re^n$ such that,

$$\psi(t_0) = x_0 \tag{32}$$

and

$$\dot{\psi}(t) = f(\psi(t), u(t), t) \qquad \forall t \in \Re \setminus \mathrm{D} . \tag{33}$$

This function $\psi(t)$ is called the *solution* through (t_0, x_0) of the ODE (30).

◆

Theorem 2. [Contraction Mapping Theorem.] If $F: \Re^n \to \Re^n$ is a local contraction map at x with contraction radius ε, then there exists a unique fixed point of F within the ε ball centered at x. I.e. there exists a unique $\sigma \in \Re^n$, $\| \sigma - x \| \le \varepsilon$, such that $\sigma = F(\sigma)$. And $\forall \sigma_0 \in \Re^n$, $\| \sigma_0 - x \| \le \varepsilon$, the sequence

$$\sigma_1 = F(\sigma_0), \sigma_2 = F(\sigma_1), \sigma_3 = F(\sigma_2), \ldots \tag{34}$$

converges to σ.

3

SDF Domain

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Contributor: *Brian Vogel*

3.1 Purpose of the Domain

The synchronous dataflow (SDF) domain is useful for modeling simple dataflow systems without complicated flow of control, such as signal processing systems. Under the SDF domain, the execution order of actors is statically determined prior to execution. This results in execution with minimal overhead, as well as bounded memory usage and a guarantee that deadlock will never occur. This domain is specialized, and may not always be suitable. Applications that require dynamic scheduling could use the process networks (PN) domain instead, for example.

3.2 Using SDF

There are four main issues that must be addressed when using the SDF domain:

- Deadlock
- Consistency of data rates
- The value of the iterations parameter
- The granularity of execution

This section will present a short description of these issues. For a more complete description, see section 3.3.

3.2.1 Deadlock

Consider the SDF model shown in figure 3.1. This actor has a feedback loop from the output of the AddSubtract actor back to its own input. Attempting to run the model results in the exception shown at the right in the figure. The director is unable to schedule the model because the input of the AddSubtract actor depends on data from its own output. In general, feedback loops can result in such condi-

tions.

The fix for such deadlock conditions is to use the SampleDelay actor, shown highlighted in figure 3.2. This actor injects into the feedback loop an initial token, the value of which is given by the *initialOutputs* parameter of the actor. In the figure, this parameter has the value {0}. This is an array with a single token, an integer with value 0. A double delay with initial values 0 and 1 can be specified using a two element array, such as {0, 1}.

It is important to note that it is occasionally necessary to add a delay that is not in a feedback loop to match the delay of an in input with the delay around a feedback loop. It can sometimes be tricky to see exactly where such delays should be placed without fully considering the flow of the initial tokens described above.

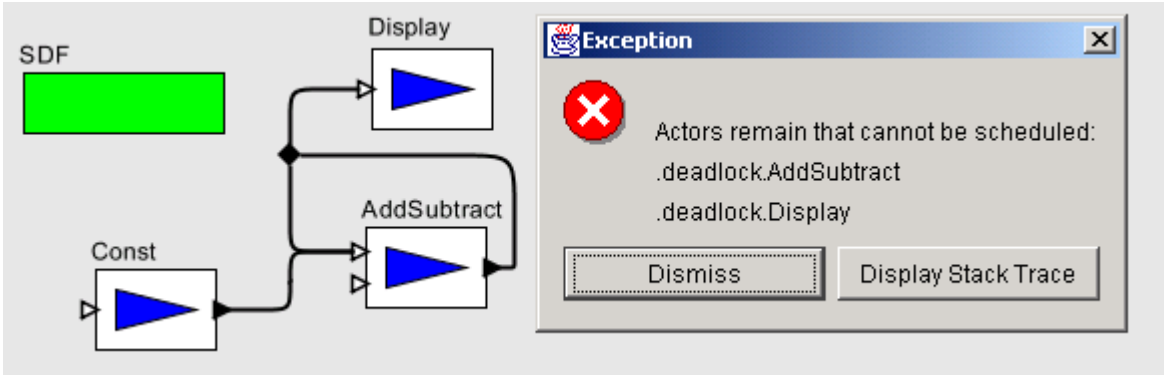

FIGURE 3.1. An SDF model that deadlocks.

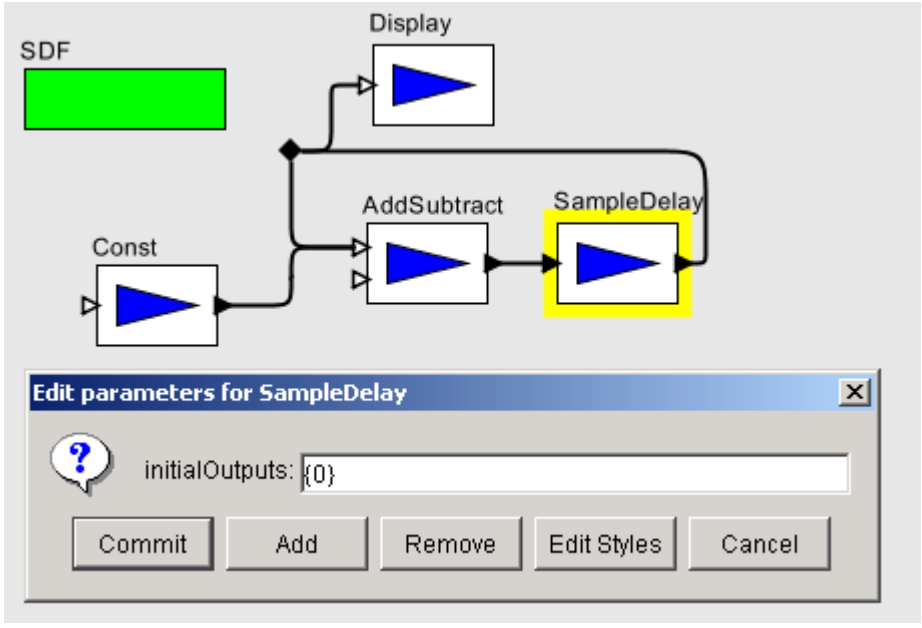

FIGURE 3.2. The model of figure 3.1 corrected with an instance of SampleDelay in the feedback loop.

3.2.2 Consistency of data rates

Consider the SDF model shown in figure 3.3. The model is attempting to plot a sinewave and its downsampled counterpart. However, there is an error because the number of tokens on each channel of the input port of the plotter can never be made the same. The DownSample actor declares that it consumes 2 tokens using the *tokenConsumptionRate* parameter of its input port. Its output port similarly declares that it produces only one token, so there will only be half as many tokens being plotted from the DownSample actor as from the Sinewave.

The fixed model is shown in figure 3.4, which uses two separate plotters. When the model is executed, the plotter on the bottom will fire twice as often as the plotter on the top, since must consume twice as many tokens. Notice that the problem appears because one of the actors (in this case, the DownSample actor) produces or consumes more than one token on one of its ports. One easy way to ensure rate consistency is to use actors that only produce and consume one token at a time. This special case is known as *homogeneous* SDF. Note that actors like the Sequence plotter which do not specify rate parameters are assumed to be homogeneous. For more specific information about the rate parame-

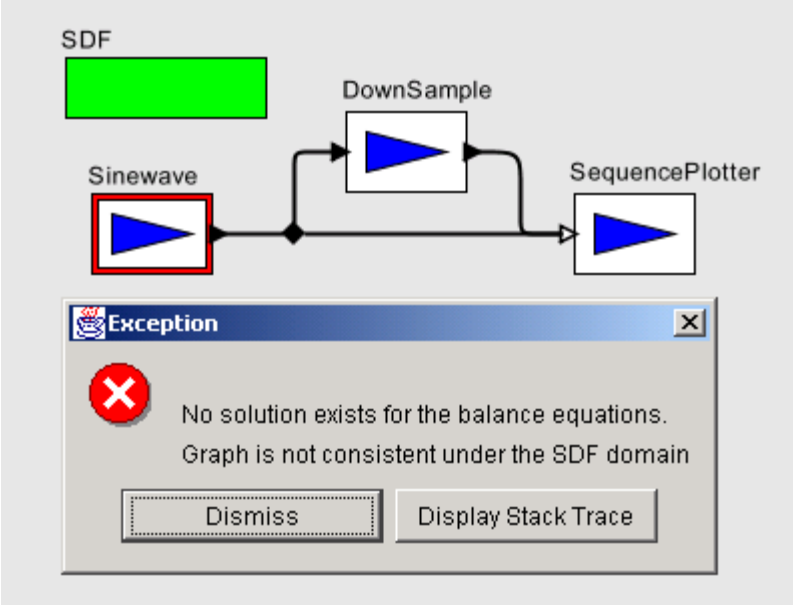

FIGURE 3.3. An SDF model with inconsistent rates.

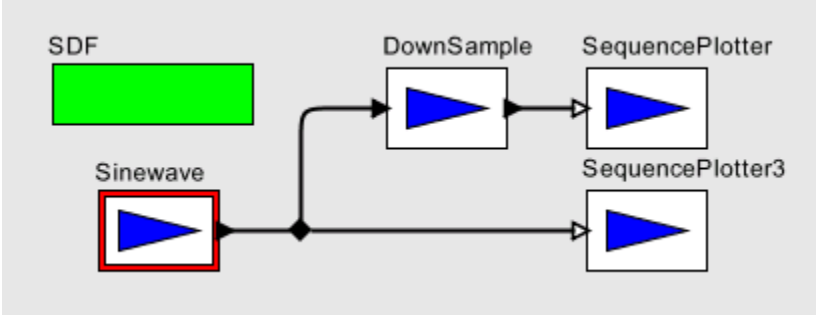

FIGURE 3.4. Figure 3.3 modified to have consistent rates.

ters and how they are used for scheduling, see section 3.3.1.

3.2.3 How many iterations?

Another issue when using the SDF domain concerns the value of the *iterations* parameter of the SDF director. In homogeneous models one token is usually produced for every iteration. However, when token rates other than one are used, more than one interesting output value may be created for each iteration. For example, consider figure 3.5 which contains a model that plots the Fast Fourier Transform of the input signal. The important thing to realize about this model is that the FFT actor declares that it consumes 256 tokens from its input port and produces 256 tokens from its output port, corresponding to an order 8 FFT. This means that only one iteration is necessary to produce all 256 values of the FFT.

Contrast this with the model in figure 3.6. This model plots the individual values of the signal. Here 256 iterations are necessary to see the entire input signal, since only one output value is plotted in each iteration.

3.2.4 Granularity

The granularity of execution of an SDF model is determined by solving a set of equations determined by declared data rates of actors, and the connections between actors. As mentioned in the previous section, this schedule may involve a small or large number of firings of each actor, depending on the relative data rates of the actors. Generally, the smallest possible valid schedule, corresponding to the smallest granularity of execution, is the most interesting. However, there some instances when this

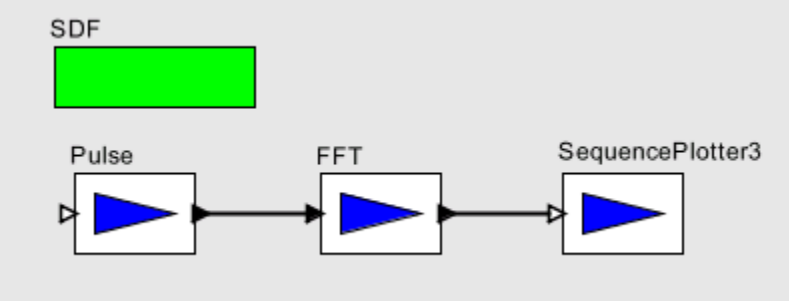

FIGURE 3.5. A model that plots the Fast Fourier Transform of a signal. Only one iteration must be executed to plot all 256 values of the FFT, since the FFT actor produces and consumes 256 tokens each firing.

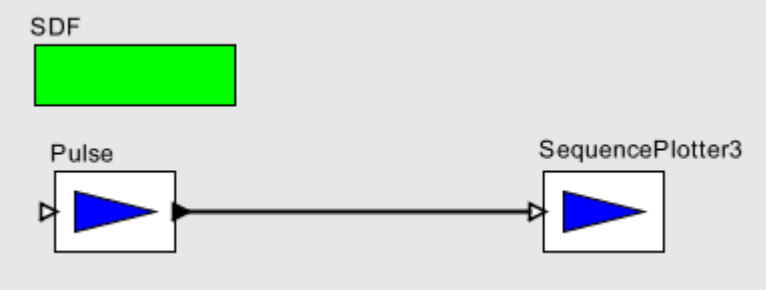

FIGURE 3.6. A model that plots the values of a signal. 256 iterations must be executed to plot the entire signal.

is not the case. In such cases the *vectorizationFactor* parameter of the SDF Directory can be used to scale up the granularity of the schedule. A *vectorizationFactor* of 2 implies that each actor is fired twice as many times as in the normal schedule.

One example when this might be useful is when modeling block data processing. For instance, we might want to build a model of a signal processing system that filters blocks of 40 samples at a time using an FIR filter. Such an actor could be written in Java, or it could be built as a hierarchical SDF model, using a single sample FIR filter, as shown in Figure 3.7. The *vectorizationFactor* parameter of the Director is set to 40. Here, each firing of the SDF model corresponds to 40 firings of the single sample FIR filter.

Another useful time to increase the level of granularity is to allow vectorized execution of actors. Some actors override the iterate() method to allow optimized execution of several consecutive firings. Increasing the granularity of an SDF model can provide more opportunities for the SDF Director to perform this optimization, especially in models that do not have fine-grained feedback.

3.3 Properties of the SDF domain

SDF is an untimed model of computation. All actors under SDF consume input tokens, perform their computation and produce outputs in one atomic operation. If an SDF model is embedded within a timed model, then the SDF model will behave as a zero-delay actor.

In addition, SDF is a statically scheduled domain. The firing of a composite actor corresponds to a single iteration of the contained(3.3.1) model. An SDF iteration consists of one execution of the pre-calculated SDF schedule. The schedule is calculated so that the number of tokens on each relation is the same at the end of an iteration as at the beginning. Thus, an infinite number of iterations can be executed, without deadlock or infinite accumulation of tokens on each relation.

Execution in SDF is extremely efficient because of the scheduled execution. However, in order to execute so efficiently, some extra information must be given to the scheduler. Most importantly, the data rates on each port must be declared prior to execution. The data rate represents the number of tokens produced or consumed on a port during every firing[1]. In addition, explicit data delays must be added to feedback loops to prevent deadlock. At the beginning of execution, and any time these data rates change, the schedule must be recomputed. If this happens often, then the advantages of scheduled execution can quickly be lost.

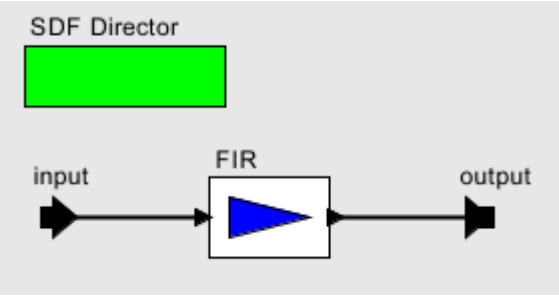

FIGURE 3.7. A model that implements a block FIR filter. The vectorizationFactor parameter of the director is set to the size of the block.

1. This is known as *multirate* SDF, where arbitrary rates are allowed. Not to be confused with *homogeneous* SDF, where the data rates are fixed to be one.

3.3.1 Scheduling

The first step in constructing the schedule is to solve the *balance equations* [71]. These equations determine the number of times each actor will fire during an iteration. For example, consider the model in figure 3.8. This model implies the following system of equations, where *ProductionRate* and *ConsumptionRate* are declared properties of each port, and *Firings* is a property of each actor that will be solved for:

$$Firings(\mathrm{A}) \times ProductionRate(\mathrm{A1}) = Firings(\mathrm{B}) \times ConsumptionRate(\mathrm{B1})$$

$$Firings(\mathrm{A}) \times ProductionRate(\mathrm{A2}) = Firings(\mathrm{C}) \times ConsumptionRate(\mathrm{C1})$$

$$Firings(\mathrm{C}) \times ProductionRate(\mathrm{C2}) = Firings(\mathrm{B}) \times ConsumptionRate(\mathrm{B2})$$

These equations express constraints that the number of tokens created on a relation during an iteration is equal to the number of tokens consumed. These equations usually have an infinite number of linearly dependent solutions, and the least positive integer solution for *Firings* is chosen as the *firing vector*, or the repetitions vector.

The second step in constructing an SDF schedule is dataflow analysis. Dataflow analysis orders the firing of actors, based on the relations between them. Since each relation represents the flow of data, the actor producing data must fire before the consuming actor. Converting these data dependencies to a sequential list of properly scheduled actors is equivalent to topologically sorting the SDF graph, if the graph is acyclic[1]. Dataflow graphs with cycles cause somewhat of a problem, since such graphs cannot be topologically sorted. In order to determine which actor of the loop to fire first, a *data delay* must be explicitly inserted somewhere in the cycle. This delay is represented by an initial token created by one of the output ports in the cycle during initialization of the model. The presence of the delay allows the scheduler to break the dependency cycle and determine which actor in the cycle to fire first. In Ptolemy II, the initial token (or tokens) can be sent from any port, as long as the port declares an *tokenInitProduction* property. However, because this is such a common operation in SDF, the Delay actor (see section 3.5) is provided that can be inserted in a feedback look to break the cycle. Cyclic graphs not properly annotated with delays cannot be executed under SDF. An example of a cyclic graph properly annotated with a delay is shown in figure 3.9.

In some cases, a non-zero solution to the balance equations does not exist. Such models are said to

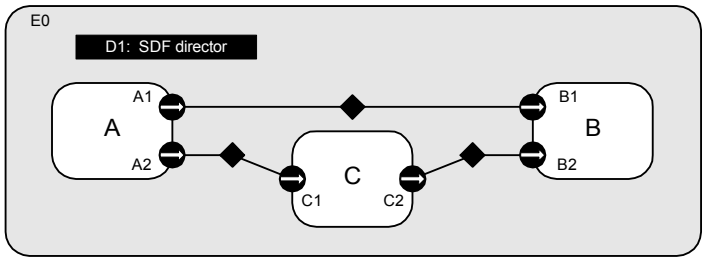

FIGURE 3.8. An example SDF model.

1. Note that the topological sort does not correspond to a unique total ordering over the actors. Furthermore, especially in multirate models it may be possible to interleave the firings of actors that fire more than once. This can result in many possible schedules that represent different performance trade-offs. We anticipate that future schedulers will be implemented to take advantage of these trade-offs. For more information about these trade-offs, see [47].

be *inconsistent*, and cannot be executed under SDF. Inconsistent graphs inevitably result in either deadlock or unbounded memory usage for any schedule. As such, inconsistent graphs are usually bugs in the design of a model. However, inconsistent graphs can still be executed using the PN domain, if the behavior is truly necessary. Examples of consistent and inconsistent graphs are shown in figure 3.10.

3.3.2 Hierarchical Scheduling

So far, we have assumed that the SDF graph is not hierarchical. The simplest way to schedule a hierarchical SDF model is flatten the model to remove the hierarchy, and then schedule the model as

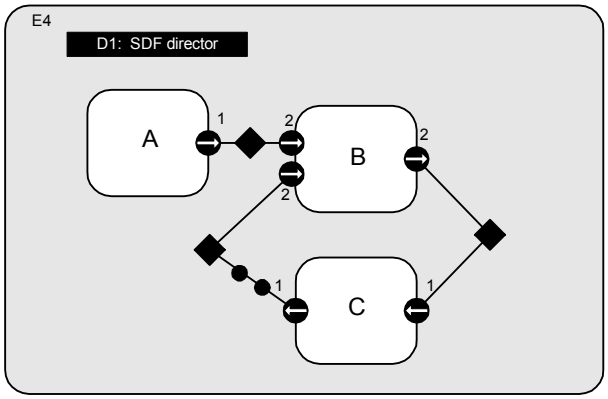

FIGURE 3.9. A consistent cyclic graph, properly annotated with delays. A one token delay is represented by a black circle. Actor C is responsible for setting the *tokenInitProduction* parameter on its output port, and creating the two tokens during initialization. This graph can be executed using the schedule A, A, B, C, C.

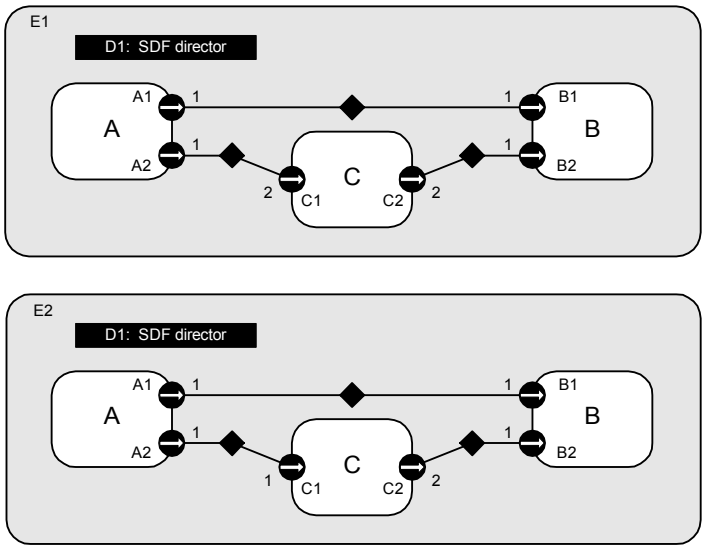

FIGURE 3.10. Two models, with each port annotated with the appropriate rate properties. The model on the top is consistent, and can be executed using the schedule A, A, C, B, B. The model on the bottom is inconsistent because tokens will accumulate between ports C2 and B2.

usual. This technique allows the most efficient schedule to be constructed for a model, and avoids certain composability problems when creating hierarchical models. In Ptolemy II, a model created using a transparent composite actor to define the hierarchy is scheduled in exactly this way.

Ptolemy II also supports a stronger version of hierarchy, in the form of opaque composite actors. In this case, the hierarchical actor appears to be no different from the outside than an atomic actor with no hierarchy. The SDF domain does not have any information about the contained model, other than the rate parameters that may be specified on the ports of the composite actor. The SDF domain is designed so that it automatically sets the rates of external ports when the schedule is computed. Most other domains are designed (conveniently enough) so that their models are compatible with default rate properties assumed by the SDF domain. For a complete description of these defaults, see the description of the SDFScheduler class in section 3.4.2.

3.3.3 Hierarchically Heterogeneous Models

An SDF model can generally be embedded in any other domain. However, SDF models are unlike most other hierarchical models in that they often require multiple inputs to be present. When building one SDF model inside another SDF model, this is ensured by the containing SDF model because of the way the data rate parameters are set as described in the previous section. For most other domains, the SDF director will check how many tokens are available on its input ports and will refuse firing (by returning false in prefire()) until enough data is present for an entire iteration to complete.

3.4 Software Architecture

The SDF kernel package implements the SDF model of computation. The structure of the classes in this package is shown in figure 3.11.

3.4.1 SDF Director

The SDFDirector class extends the StaticSchedulingDirector class. When an SDF director is created, it is automatically associated with an instance of the default scheduler class, SDFScheduler. This scheduler is intended to be relatively fast, but not designed to optimize for any particular performance goal. The SDF director does not currently restrict the schedulers that may be used with it. For more information about SDF schedulers, see section 3.4.2.

The director has a parameter, *iterations*, which determines a limit on the number of times the director wishes to be fired[1]. After the director has been fired the given number of times, it will always return false in its postfire() method, indicating that it does not wish to be fired again. The *iterations* parameter must contain a non-negative integer value. The default value is an IntToken with value 0, indicating that there is no preset limit for the number of times the director will fire. Users will likely specify a non-zero value in the director of the toplevel composite actor as the number of toplevel iterations of the model.

The SDF director also has a *vectorizationFactor* parameter that can be used to request vectorized execution of a model. This parameter increases the granularity of the executed schedule so that the director fires each actor *vectorizationFactor* times more than would be normal. The *vectorizationFactor* parameter must contain a positive integer value. The default value is an IntToken with value one, indicating that no vectorization should be done. Changing this parameter changes the meaning of an

1. This parameter acts similarly to the Time-to-Stop parameter in Ptolemy Classic.

embedded SDF model and may cause deadlock in a model that uses it. On the other hand, increasing the *vectorizationFactor* may increase the efficiency of a model, both by reducing the number of times the SDF model needs to be executed, and by allowing the SDF model to combine multiple firings of contained actors using the iterate() method.

The newReceiver() method in SDF directors is overloaded to return instances of the SDFReceiver class. This receiver contains optimized method for reading and writing blocks of tokens. For more information about SDF receivers, see section 3.4.3.

3.4.2 SDF Scheduler

The basic SDFScheduler derives directly from the Scheduler class. This scheduler provides unlooped, sequential schedules suitable for use on a single processor. No attempt is made to optimize

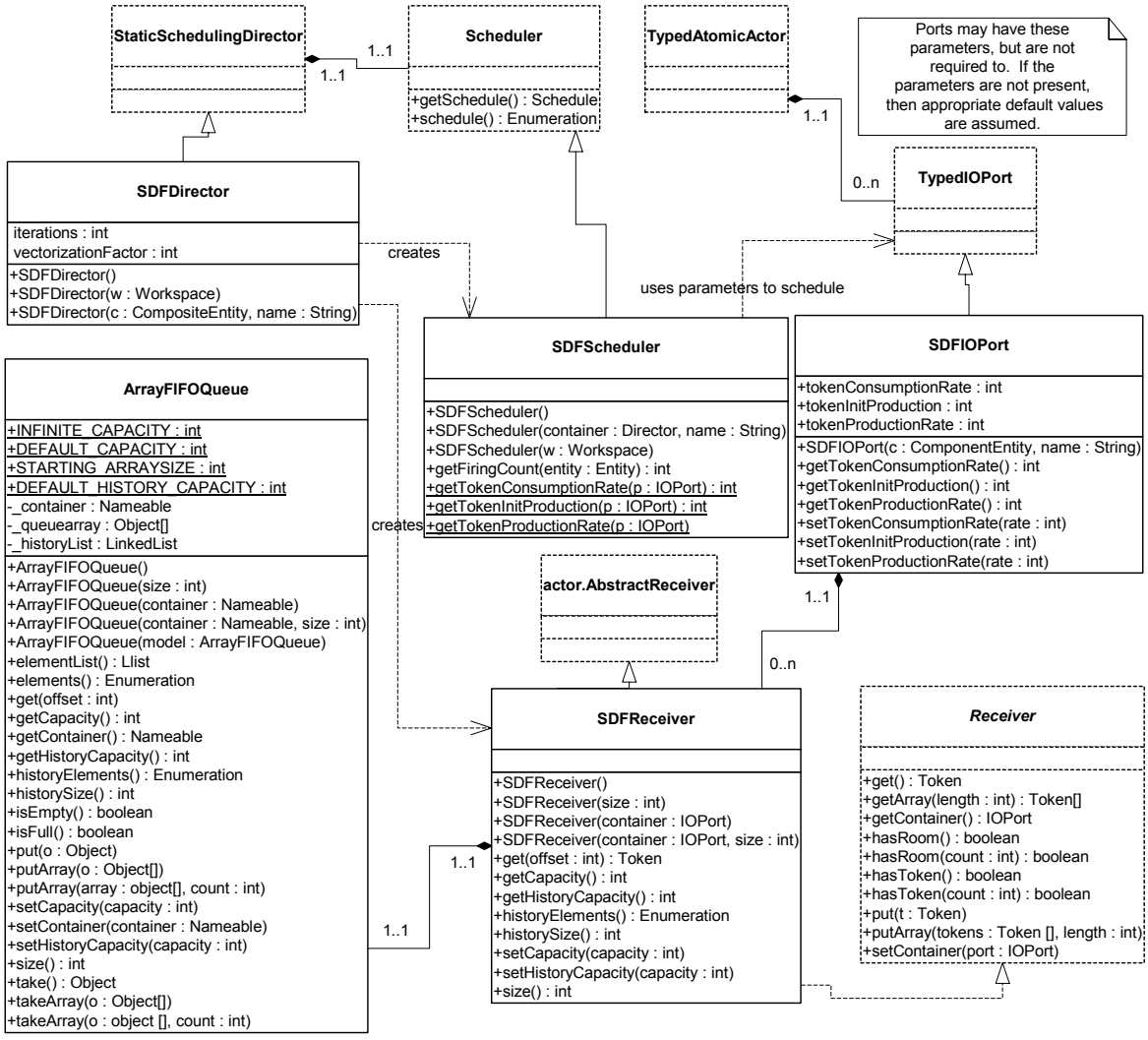

FIGURE 3.11. The static structure of the SDF kernel classes.

the schedule by minimizing data buffer sizes, minimizing the size of the schedule, or detecting parallelism to allow execution on multiple processors. We anticipate that more elaborate schedulers capable of these optimizations will be added in the future.

The scheduling algorithm is based on the simple multirate algorithm in [71]. Currently, only single processor schedules are supported. The multirate scheduling algorithm relies on the actors in the system to declare the data rates of each port. The data rates of ports are specified using three parameters on each port named *tokenConsumptionRate*, *tokenProductionRate*, and *tokenInitProduction*. The production parameters are valid only for output ports, while the consumption parameter is valid only for input ports. If a parameter exists that is not valid for a given port, then the value of the parameter must be zero, or the scheduler will throw an exception. If a valid parameter is not specified when the scheduler runs, then default values of the parameters will be assumed, however the parameters are not then created[1].

After scheduling, the SDF scheduler will set the rate parameters on any external ports of the composite actor. This allows a containing actor, which may represent an SDF model, to properly schedule the contained model, as long as the contained model is scheduled first. To ensure this, the SDF director forces the creation of the schedule after initializing all the actors in the model. The SDF scheduler also sets attributes on each relation that give the maximum buffer size of the relation. This can be useful feedback for analyzing deadlocks, or for visualization.This mechanism is illustrated in the sequence diagram in figure 3.12.

SDF graphs should generally be connected. If an SDF graph is not connected, then there is some concurrency between the disconnected parts that is not captured by the SDF rate parameters. In such cases, another model of computation (such as process networks) should be used to explicitly specify the concurrency. As such, the SDF scheduler by default disallows disconnected graphs, and will throw an exception if you attempt to schedule such a graph. However, sometimes it is useful to avoid introducing another model of computation, or to allow dynamic modifications to an executing model. By setting the *allowDisconnectedGraphs* parameter of the SDF director to true, the scheduler will assume a default notion of concurrency between different parts of a model. Each disconnected ‘island’ will be scheduled independently, and an overall schedule created that includes one execution of the schedule for each island.

Multiports. Notice that it is impossible to set a rate parameter on individual channels of a port. This is intentional, and all the channels of an actor are assumed to have the same rate. For example, when the AddSubtract actor fires under SDF, it will consume exactly one token from each channel of its input *plus* port, consume one token from each channel of its *minus* port, and produce one token the single channel of its *output* port. Notice that although the domain-polymorphic adder is written to be more general than this (it will consume *up to* one token on each channel of the input port), the SDF scheduler will ensure that there is always at least one token on each input port before the actor fires.

Dangling ports. All channels of a port are required to be connected to a remote port under the SDF domain. A regular port that is not connected will always result in an exception being thrown by the scheduler. However, the SDF scheduler detects multiports that are not connected to anything (and thus have zero width). Such ports are interpreted to have no channels, and will be ignored by the SDF scheduler.

1. The assumed values correspond to a homogeneous actor with no data delay. Input ports are assumed to have a consumption rate of one, output ports are assumed to have a production rate of one, and no tokens are produced during initialization.

3.4.3 SDF ports and receivers

Unlike most domains, multirate SDF systems tend to produce and consume large blocks of tokens during each firing. Since there can be significant overhead in data transport for these large blocks, SDF receivers are optimized for sending and receiving a block of tokens *en masse*.

The SDFReceiver class implements the Receiver interface. Instead of using the FIFOQueue class to store data, which is based on a linked list structure, SDF receivers use the ArrayFIFOQueue class, which is based on a circular buffer. This choice is much more appropriate for SDF, since the size of the buffer is bounded, and can be determined statically[1].

The SDFIOPort class extends the TypedIOPort class. It exists mainly for convenience when creating actors in the SDF domain. It provides convenience methods for setting and accessing the rate parameters used by the SDF scheduler.

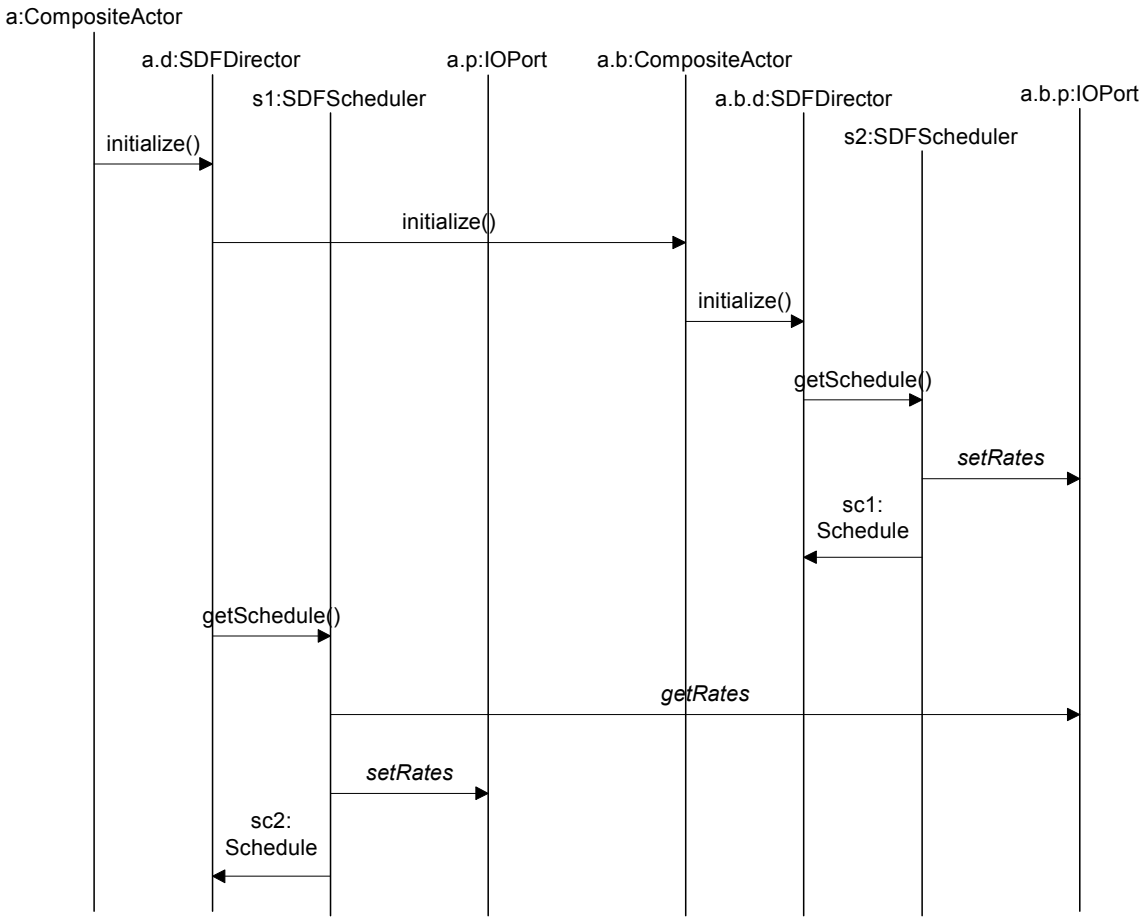

FIGURE 3.12. The sequence of method calls during scheduling of a hierarchical model.

1. Although the buffer sizes can be statically determined, the current mechanism for creating receivers does not easily support it. The SDF domain currently relies on the buffer expanding algorithm that the ArrayFIFOQueue uses to implement circular buffers of unbounded size. Although there is some overhead during the first iteration, the overhead is minimal during subsequent iterations (since the buffer is guaranteed never to grow larger).

3.4.4 ArrayFIFOQueue

The ArrayFIFOQueue class implements a first in, first out (FIFO) queue by means of a circular array buffer[1]. Functionally it is very similar to the FIFOQueue class, although with different enqueue and dequeue performance. It provides a token history and an adjustable, possibly unspecified, bound on the number of tokens it contains.

If the bound on the size is specified, then the array is exactly the size of the bound. In other words, the queue is full when the array becomes full. However, if the bound is unspecified, then the circular buffer is given a small starting size and allowed to grow. Whenever the circular buffer fills up, it is copied into a new buffer that is twice the original size.

3.5 Actors

Most domain-polymorphic actors can be used under the SDF domain. However, actors that depend on a notion of time may not work as expected. For example, in the case of a TimedPlotter actor, all data will be plotted at time zero when used in SDF. In general, domain-polymorphic actors (such as AddSubtract) are written to consume at most one token from each input port and produce exactly one token on each output port during each firing. Under SDF, such an actor will be assumed to have a rate of one on each port, and the actor will consume exactly one token from each input port during each firing. There is one actor that is normally only used in SDF: the SampleDelay actor. This actor is provided to make it simple to build models with feedback, by automatically handling the *tokenInitProduction* parameter and providing a way to specify the tokens that are created.

SampleDelay

Ports: *input* (Token), *output* (Token).
Parameters: *initialOutputs* (ArrayToken).

During initialization, create a token on the output for each token in the *initialOutputs* array. During each firing, consume one token on the input and produce the same token on the output.

1. Adding an array of objects to an ArrayFIFOQueue is implemented using the java.lang.system.arraycopy method. This method is capable of safely removing certain checks required by the Java language. On most Java implementations, this is significantly faster than a hand coded loop for large arrays. However, depending on the Java implementation it could actually be slower for small arrays. The cost is usually negligible, but can be avoided when the size of the array is small and known when the actor is written.

4

FSM Domain

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Edward A. Lee
Haiyang Zheng

4.1 Introduction

Finite state machines (FSMs) have been used extensively in designing sequential control logic. There are two major reasons behind their use. First, FSMs are a very intuitive way to capture control logic and make it easier to communicate a design. Second, FSMs have been the subject of a long history of research work. Many formal analysis and verification methods have been developed for them.

In their simple flat form, FSM models have a key weakness: the number of states in an FSM model can get quite large even for a moderately complex system. Such models quickly become chaotic and incomprehensible when one tries to model a system having many concurrent activities. The problem can be solved by introducing hierarchical organization into FSM models and using them in combination with concurrency models. David Harel first used this approach when he introduced the *Statecharts* formalism [41].

The Statecharts formalism extends the conventional FSM model in three aspects: hierarchical decomposition of states, concurrent composition of FSMs in a synchronous-reactive fashion, and a broadcast communication mechanism between concurrent components. While how these extensions fit together was not completely specified in [41], Harel's work stimulated a lot of interest in the approach. Consequently, there is a proliferation of variants of the Statecharts formalism [10], each proposing a different way to make the extensions fit into a monolithic model. Unfortunately, in all these variants FSM is combined with a particular concurrency model. The applicability of the resulting models is often limited.

Based on the Ptolemy philosophy of hierarchical composition of heterogeneous models of computation, the **charts*[1] formalism [37] allows embedding hierarchical FSMs within a variety of concurrency models. If tight synchronization is possible and desirable, then FSMs can be composed by the synchronous-reactive model. If the system has a global notion of time and components communicate

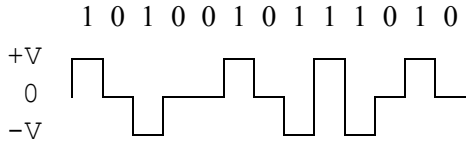
by time-stamped events, then FSMs can be composed by the discrete-event model. The rest of this chapter focuses on how the FSM domain in Ptolemy II supports the *charts formalism.

4.2 Building FSMs in Vergil

An FSM model is contained by an instance of FSMActor. The FSM model reacts to inputs to the FSM actor by making state transitions. Actions such as sending tokens to the output ports of the FSM actor can be associated with state transitions. In this section, we show how to construct and run a model with an FSM actor in Vergil.

4.2.1 Alternate Mark Inversion Coder

Alternate Mark Inversion (AMI) is a simple digital transmission technique that encodes a bit stream on a signal line as shown below:



The 0 bits are transmitted with voltage zero. The 1 bits are transmitted alternately with positive and negative voltages. On average, the resulting waveform will have no DC component.

We can model an AMI coder with a two-state FSM shown in figure 4.2. To construct a Ptolemy II model containing this coder, follow these steps:

1. Start Vergil, open a graph editor by selecting File -> New -> Graph Editor.
2. From more libraries/automata in the palette on the left, drag an FSM actor to the graph. Rename the FSM actor AMICoder.
3. Right click on AMICoder, select Configure Ports. Add an input port with name *in* and an output port with name *out* to AMICoder.
4. Right click on AMICoder, select Look Inside. This will open an FSM editor for AMICoder. Note that the ports of AMICoder are placed at the upper left corner of the graph panel.
5. From the palette on the left, drag a state to the graph, rename it Positive. Drag another state to the graph, rename it Negative.
6. Control-drag from the Positive state to the Negative state to create a transition.
7. Double click on the transition. This will bring up the dialog box shown in figure 4.1 for editing the parameters of the transition.
8. Set guardExpression to `in == 1`, and outputActions to `out = 1`.
9. Create a transition from the Positive state back to itself with guard expression `in == 0` and output action `out = 0`.

1. Pronounced “starcharts.” The star represents a wildcard that can be interpreted as matching multiple concurrency models.

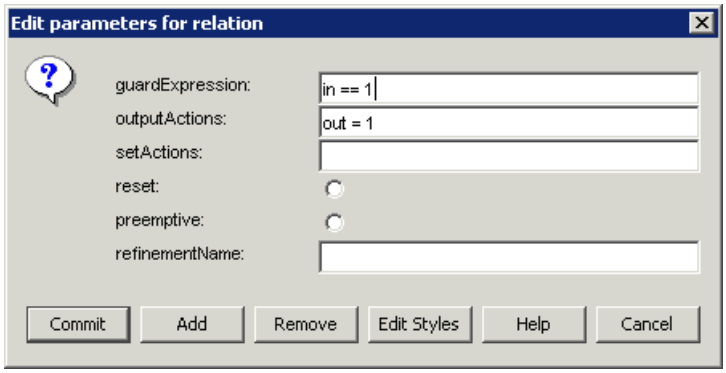


FIGURE 4.1. The dialog box for editing parameters of a transition.

10. Create a transition from the Negative state back to itself with guard expression `in == 0` and output action `out = 0`.
11. Create a transition from the Negative state to the Positive state with guard expression `in == 1` and output action `out = -1`.
12. Right click on the background of the graph panel. Select Edit Parameters from the context menu. This will bring up the dialog box for editing parameters of AMICoder. Set initialStateName to `Positive`.
13. The construction of AMICoder is complete. It will look like what is shown in figure 4.2.
14. Return to the graph editor opened in step 1.
15. Drag a Pulse actor (from actor library, sources), a SequencePlotter (from actor library, sinks), and an SDF director (from director library) to the graph.
16. Connect the actors as shown in figure 4.3.

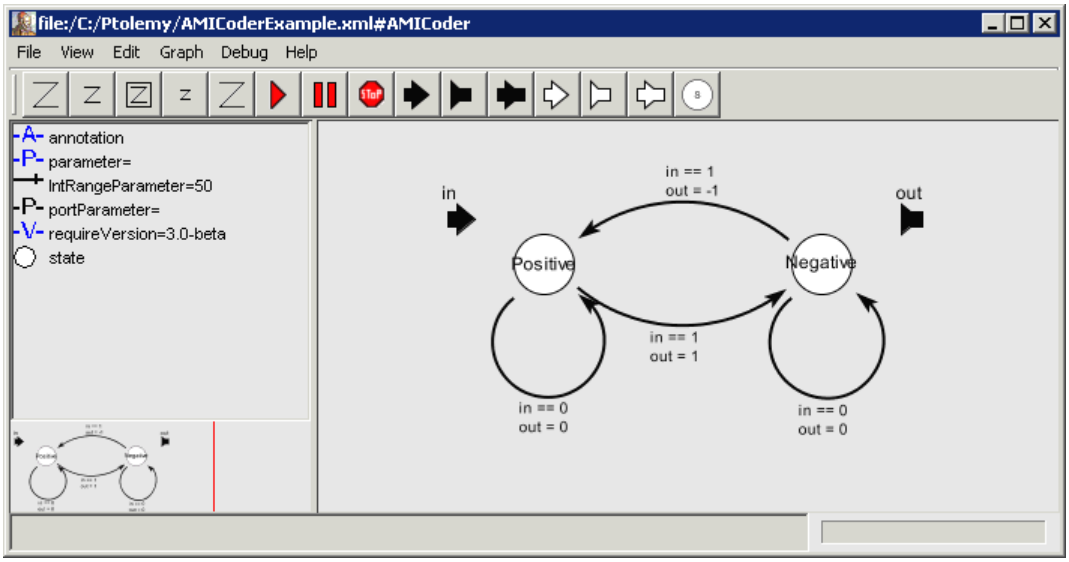


FIGURE 4.2. Vergil FSM editor showing the AMICoder.

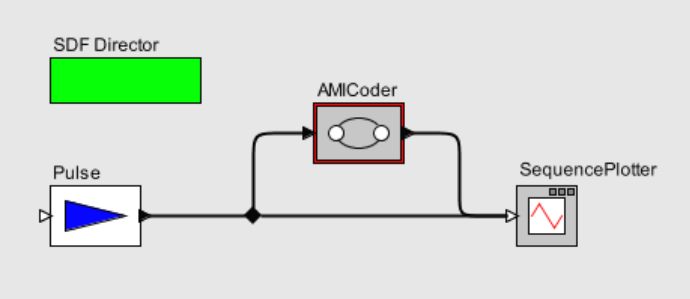


FIGURE 4.3. An SDF model with the AMICoder.

17. Edit parameters of the Pulse actor: set indexes to `{0, 1, 2, 3, 4, 5}`; set values to `{0, 1, 1, 1, 0, 1}`.
18. The model construction is complete.
19. Select View -> Run Window from the menu. Set director iterations to `6` and execute the model. For a better display of the result, open the set plot format dialog box, unselect connect and use various marks.

4.3 The Implementation of FSMActor

The FSMActor-related classes in the FSM kernel package are shown in figure 4.4.

The FSMActor class extends the CompositeEntity class and implements the TypedActor interface. An FSM actor contains states and transitions. The State class is a subclass of ComponentEntity. A State has two ports: incomingPort, which links to incoming transitions to the state, and outgoingPort, which links to transitions going out from the state. The Transition class is a subclass of ComponentRelation. A transition links to exactly two ports: the outgoing port of its source state, and the incoming port of its destination state.

4.3.1 Guard Expressions

The guard of a transition is specified by its *guardExpression* string attribute. Guard expressions are parsed and evaluated using the Ptolemy II expression language (see the Expressions chapter and the Data chapter for details). Guard expressions should evaluate to a boolean value. A transition is enabled if its guard expression evaluates to true. Parameters of the FSM actor and input variables (defined below) can be used in guard expressions.

Input variables represent the status and input value for each input port of the FSM actor. If the input port is a single port, two variables are used: a status variable named *portName*`_isPresent`, and a value variable named *portName*. If the input port is a multiport of width *n*, *2n* variables are used, two for each channel: a status variable named *portName_channelIndex*`_isPresent`, and a value variable named *portName_channelIndex*. The status variables will have boolean value true if there is a token at the corresponding input, or false otherwise. The value variables have the same type as the corresponding input, and contain the token received from the input, or null if there is no token. All input variables are contained by the FSM actor.

In the following examples (and the examples in the next section), we assume that the FSM actor has two input ports: a single port *in1* and a multiport *in2* of width 2; an output port *out* that is a multi-

port of width 2; and a parameter *param*.

- Guard expression: `in2_0 + in2_1 > 10`. If the inputs from the two channels of port *in2* have a total greater than 10, the transition is enabled. Note that if one or both channels of port *in2* do not have a token when this expression is evaluated, an exception will be thrown.
- Guard expression: `in1_isPresent && in1 > param`. If there is input from port *in1* and the value of the input is greater than *param*, the transition is enabled.

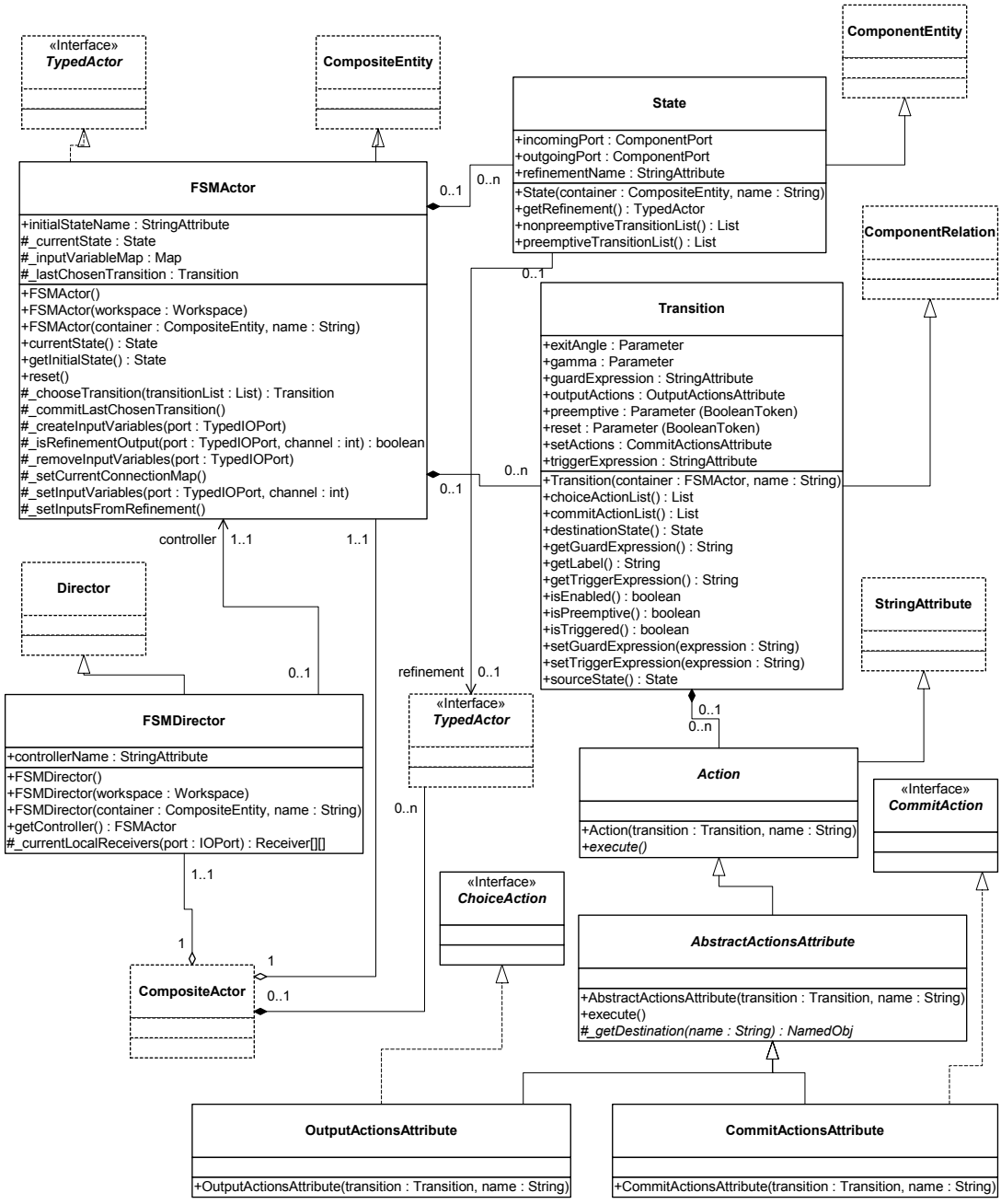


FIGURE 4.4. The UML static structure diagram of FSMActor-related classes.

4.3.2 Actions

A transition can have a set of actions that produce output tokens or set parameters of the FSM actor. To make FSM actors domain polymorphic (see section 4.5), especially for them to be operational in domains having fixed-point semantics, two kinds of actions are defined: choice actions and commit actions. Choice actions do not modify the extended state[1] of the FSM actor. They are executed when the FSM actor is fired and the containing transition is enabled. Commit actions may modify the extended state of the FSM actor. They are executed in postfire() if the containing transition was enabled in the last firing of the FSM actor. Two marker interfaces are defined in the FSM kernel package: ChoiceAction, which is implemented by all choice action classes, and CommitAction, implemented by all commit action classes.

A transition has an *outputActions* attribute which is an instance of OutputActionsAttribute. The OutputActionsAttribute class allows the user to specify a list of semicolon separated output actions of the form `destination = expression`. The expression can use parameters of the FSM actor and input variables. The destination is either a port name, in which case the result token from evaluating the expression is broadcast to all channels of the port, or of the form `portName(channelIndex)`, in which case the result token is sent to the specified channel. Output actions are choice actions.

- outputActions: `out = in1_isPresent ? in1 : 0`. Broadcast the input from port *in1*, or 0 if there is no input from *in1*, to the two channels of *out*.
- outputActions: `out(0) = param; out(1) = param + 1`. Send the value of *param* to the first channel of *out*, and the value of *param* plus 1 to the second channel.

A transition has a *setActions* attribute which is an instance of CommitActionsAttribute. The CommitActionsAttribute class allows the user to specify a list of semicolon separated commit actions of the form `destination = expression`. The expression can use parameters of the FSM actor and input variables. The destination is a parameter name.

- setActions: `param = param + (in1_isPresent ? in1 : 0)`. The input values from port *in1* are accumulated in *param*.

It is worth noting that parameter values are persistent. If not properly initialized, the parameter *t* in the above example will retain its accumulated value from previous model executions. A useful approach is to build the FSM model such that the initial state has an outgoing transition with guard expression `true`, and use the set actions of this transition for parameter initialization.

4.3.3 Execution

The methods that define the execution of an FSM actor are implemented as follows:

- `preinitialize()`: create receivers and input variables for each input port; set current state to the initial state as specified by the *initialStateName* attribute.
- `initialize()`: perform domain-specific initialization by calling the initialize(Actor) method of the director. Note that in the example given in section 4.2.1, the director will be the SDF director.
- `prefire()`: always return true. An FSM actor is always ready to fire.
- `fire()`: set the values of input variables; choose the enabled transition among the outgoing transitions of the current state; execute the choice actions of the chosen transition.
- `postfire()`: execute the commit actions of the last chosen transition; change state to the destina-

1. The extended state of an FSM actor is the current state of the state machine it contains plus the set of current values of its parameters.

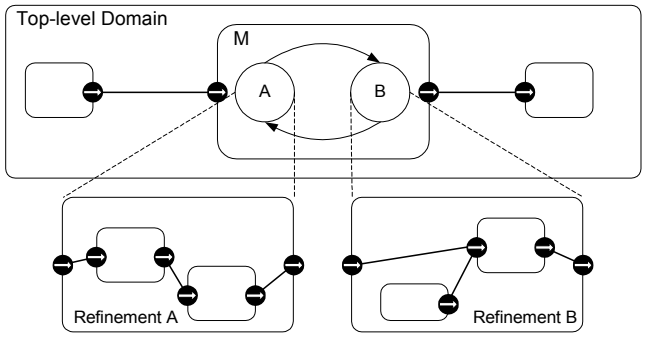


FIGURE 4.5. A modal model example.

tion state of that transition. If the destination state is a final state as specified by the *finalStateNames* attribute, then return false to inform the director not to fire this actor again.

Non-deterministic FSMs are not allowed[1]. The fire() method checks whether there is more than one enabled transition from the current state. An exception is thrown if there is. In the case when there is no enabled transition, the FSM will stay in its current state.

4.4 Modal Models

The FSM domain supports the *charts formalism with modal models. The concept of modal model is illustrated in figure 4.5. *M* is a modal model with two operation modes. The modes are represented by states of an FSM that controls mode switching. Each mode has a refinement that specifies the behavior of the mode. In Ptolemy II, a modal model[2] is constructed in a modal model actor having the FSM director as local director. The modal model actor contains a mode controller (an FSM actor) and a set of actors that model the refinements. The FSM director mediates the interaction with the outside domain, and coordinates the execution of the refinements with the mode controller.

4.4.1 A Schmidt Trigger Example

In this section, we will illustrate how to build a modal model in Ptolemy II with a simple Schmidt trigger example. The output from the Schmidt trigger will move from -1.0 to 1.0 when its input becomes greater than 0.3, and will move back to -1.0 once its input becomes less than -0.3.

1. Open a Vergil graph editor. From utilities, drag a modal model actor to the graph, rename it SchmidtTrigger. Add an input port named *in* and an output port named *out* to it.

2. Look inside SchmidtTrigger. This will open an FSM editor for the mode controller. Construct a two-state FSM as shown in figure 4.6. Set the *reset* parameter of both transitions to `true`. Set initial state name of the mode controller to `N`.

3. Right click on the state named `P`, select Add Refinement. Specify the name of the refinement as RefinementP. A Vergil graph editor will be opened for the refinement. Build a model for it as shown in figure 4.7. Set the value of Const to `1.0`. Edit parameters of Pulse: set indexes to

1. This may change in future developments.
2. The current software architecture that supports modal models is experimental. A new approach based on higher order functions is in progress.

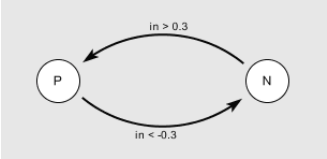


FIGURE 4.6. The mode controller for SchmidtTrigger.

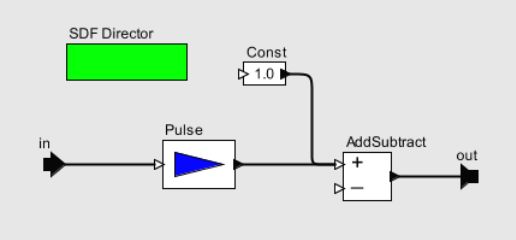


FIGURE 4.7. Model for the refinements in SchmidtTrigger.

`{0, 1, 2, 3, 4}`, and values to `{-2.0, -1.6, -1.2, -0.8, -0.4}`.

4. Add a refinement named RefinementN to state `N`. Build a model for it similar to the one shown in figure 4.7. Set the value of Const to `-1.0`. Edit parameters of Pulse: set indexes to `{0, 1, 2, 3, 4}`, and values to `{2.0, 1.6, 1.2, 0.8, 0.4}`.

5. Back to the graph editor opened in step 1. Build the model as shown in figure 4.8. The model generates an input signal (a sinusoid plus Gaussian noise) for the SchmidtTrigger and plots its output. Edit parameters of Ramp: set init to `-PI/2`, and step to `PI/20`. Edit parameters of Gaussian: set standardDeviation to `0.2`.

6. Run the model for 200 iterations. A sample result is shown in figure 4.9.

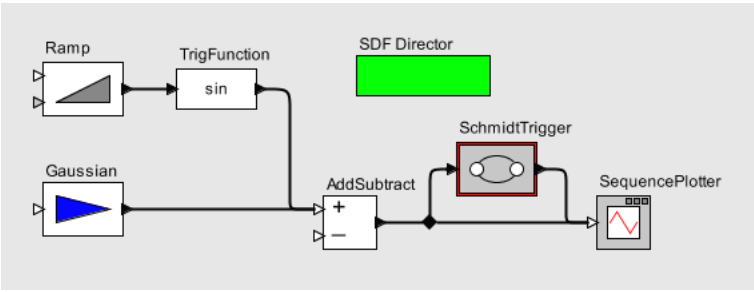


FIGURE 4.8. The top-level model with the SchmidtTrigger.

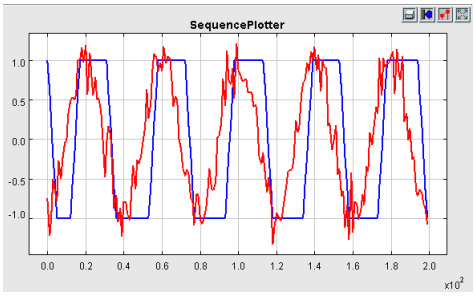


FIGURE 4.9. Sample result of the model shown in figure 4.8.

4.4.2 Implementation

The classes in the FSM kernel package that support modal models are shown in figure 4.10. The execution of a modal model is summarized below.

When a modal model is fired:

1. The FSM director transfers the input tokens from the outside domain to the mode controller and to the refinement of its current state.
2. The preemptive transitions from the current state of the mode controller are examined. If there is an enabled transition, execute the choice actions of the transition, go to step 5.
3. Fire the refinement of the current state.
4. The non-preemptive transitions from the current state of the mode controller are examined. If there is an enabled transition, execute the choice actions of the transition.
5. Any output token produced by the mode controller or the refinement is transferred to the outside domain.

To make a transition preemptive, set its *preemptive* parameter to true. The mode controller does not change state during successive firings in one iteration in order to support outside domains that iterate to a fixed point. In postfire(), if there is an enabled transition in the latest firing:

1. Execute the commit actions of the transition.
2. Set the current state of the mode controller to the destination state of the transition.
3. If the value of the *reset* parameter of the transition is true, the refinement of the destination state is initialized.

4.4.3 Applications

Hybrid System Modeling. An HSDirector class that extends the FSMDirector class is created for modeling hybrid systems with FSMs and continuous-time (CT) models. An example is presented in section

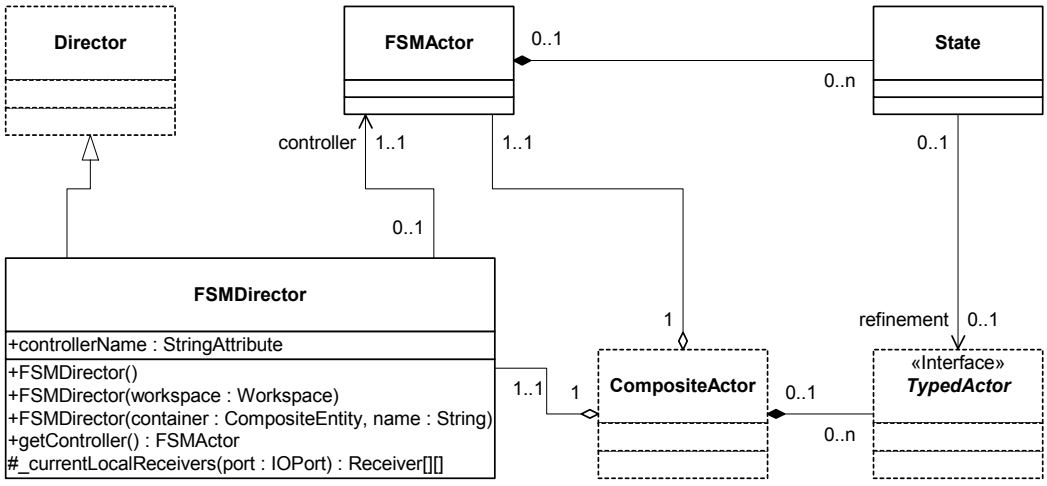


FIGURE 4.10. FSM kernel classes that support modal models.

2.7.3. Execution control is discussed in section 2.8.6.

Communication Protocol Modeling. Hierarchical FSMs are used to model protocol control logic. The timing characteristics of the communication channel are captured by discrete-event (DE) models. We have applied this approach to the alternating bit protocol. The detailed models can be found in the FSM domain demo directory ($PTII/ptolemy/domains/fsm/demo/ABP).

5

Giotto Domain

Authors: *Haiyang Zheng*
Edward Lee
Christoph Kirsch

5.1 Introduction

The Giotto model is a semantic model that describes the communication between periodic time triggered components. It was developed by Thomas Henzinger and his group. It was designed for deterministic and safety critical applications.

The main points about the Giotto model are:

1. A Giotto model is composed of one or more *modes* and each mode is composed of several *tasks*.

2. For every task, the design specifies a worst case execution time (WCET) which constrains the execution time of that task in the model.

3. Tasks are concurrent and preemptable.

4. Each task may consume some tokens and produce some tokens for other actors or itself, the produced tokens are not available until the end of the task's execution.

5. Mode switching includes invoking or terminating some tasks.

6. There are constraints on mode switching, e.g., the states consistency of tasks.

More details of the Giotto model may be found at http://www-cad.eecs.berkeley.edu/~fresco/giotto.

5.2 Using Giotto

The execution time of an actor in the Giotto model is defined as the *period* (a parameter of the Giotto Director) divided by the *frequency* (a parameter associated with the actor). To configure the period of a Giotto model, modify the value of the period parameter. The default value of period is 0.1 sec. To configure the frequency of a task, add a parameter called *frequency* (the value has to be an inte-

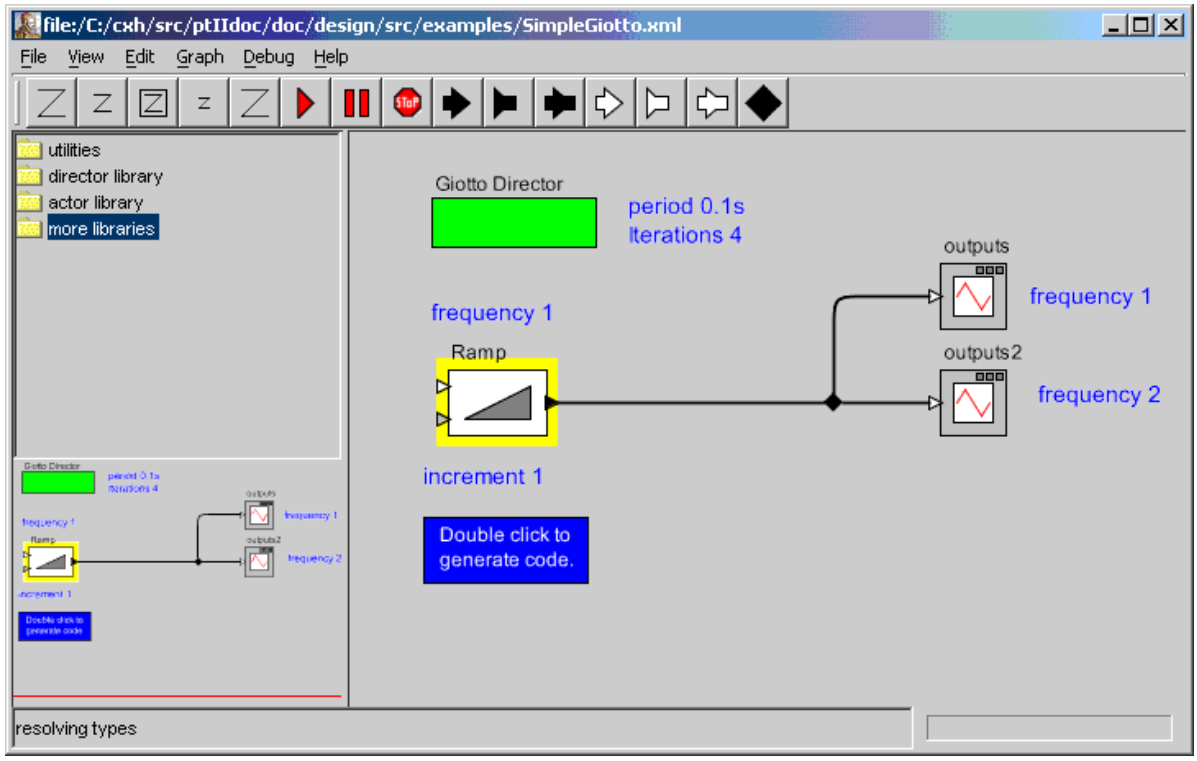


FIGURE 5.1. A Simple Giotto model with only one mode.

ger). Without the explicit frequency parameter, the director assigns a default frequency 1 to the actor.

There is also an *iterations* parameter associated with the director, which is used to control the number of iterations of the model, or the total execution time of the model. The default value is 0, which means that the model executes forever.

There is one constraint when constructing models: each channel of an input port must have exactly one source. This ensures the determinacy of the model.

Figure 5.1 is a simple Giotto model. The simulation result of this model is shown in Figure 5.2. The blue box in Figure 5.1 is GiottoCodeGenerator. It is used to generate Giotto code for the E-Compiler for schedulability analysis. To use the GiottoCodeGenerator, drag the *CodeGenerator* into the graph editor from the tools on the left side under the directory *more libraries/experimental domains/Giotto*. Double clicking this icon will pop up a text window with the generated code. The generate code for Figure 5.1 is shown in Figure 5.3.

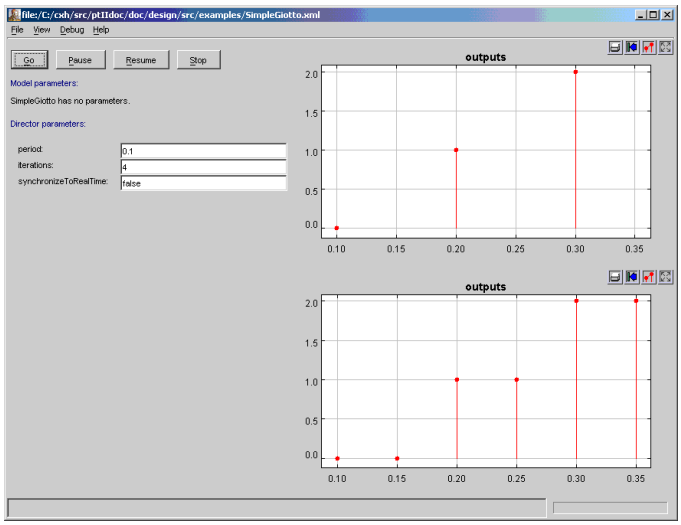


FIGURE 5.2. Simulation results for the model in Figure 5.1

```
sensor
actuator
output
  Token_port Ramp_output := CGinit_Ramp_output;
task Ramp (Token_port Ramp_trigger,Token_port
Ramp_step)
        output (Ramp_output)
        state ()
{
        schedule
CGRamp_Task(Ramp_trigger,Ramp_step,Ramp_output)
}
task outputs (Token_port outputs_input)
        output ()
        state ()
{
        schedule CGoutputs_Task(outputs_input,)
}
task outputs2 (Token_port outputs2_input)
        output ()
        state ()
{
        schedule
CGoutputs2_Task(outputs2_input,)
}
driver Ramp_driver ()
        output (Token_port
Ramp_trigger,Token_port Ramp_step)
{
}
driver outputs_driver (Ramp_output)
        output (Token_port outputs_input)
{
          if constant_true() then
copy_Token_port( Ramp_output, outputs_input)
}
driver outputs2_driver (Ramp_output)
        output (Token_port outputs2_input)
{
          if constant_true() then
copy_Token_port( Ramp_output, outputs2_input)
}
start SimpleGiotto {
  mode SimpleGiotto () period 100 {
    taskfreq 1 do Ramp(Ramp_driver);
    taskfreq 1 do outputs(outputs_driver);
    taskfreq 2 do outputs2(outputs2_driver);
  }
}
```

FIGURE 5.3. Generated Giotto code for the model in Figure 5.1

5.3 Interacting with Other Domains

During the design of real applications, big models are often decomposed into smaller models, each having their own model of computation. So, it is important to study the interactions between Giotto models and other models. A few discussions and examples are given in the following paragraphs.

5.3.1 Giotto Embedded in DE and CT

The interface between DE model and Giotto model is well defined. Embedded inside DE model, the Giotto model could easily be invoked to meet design requirements. The composite model gives a paradigm of asynchronous Giotto model triggered by discrete events compared with the normal Giotto model triggered by periodic time.

Figure 5.4 shows a Giotto model composed inside a DE model, which can be found at $PTII/ptolemy/domains/giotto/demo/Composite/Composite.xml. The details of the DE domain are in Chapter 14. The Giotto model runs with period 0.2 sec. and iterates twice each time it is invoked. There are two triggering events: one happens at time 0.0 sec. and the other at time 1.0 sec. The result is shown in Figure 5.5. The results in the *State* plot have a delay of 0.2 sec. with respect to the triggering events in the *Events* plot.

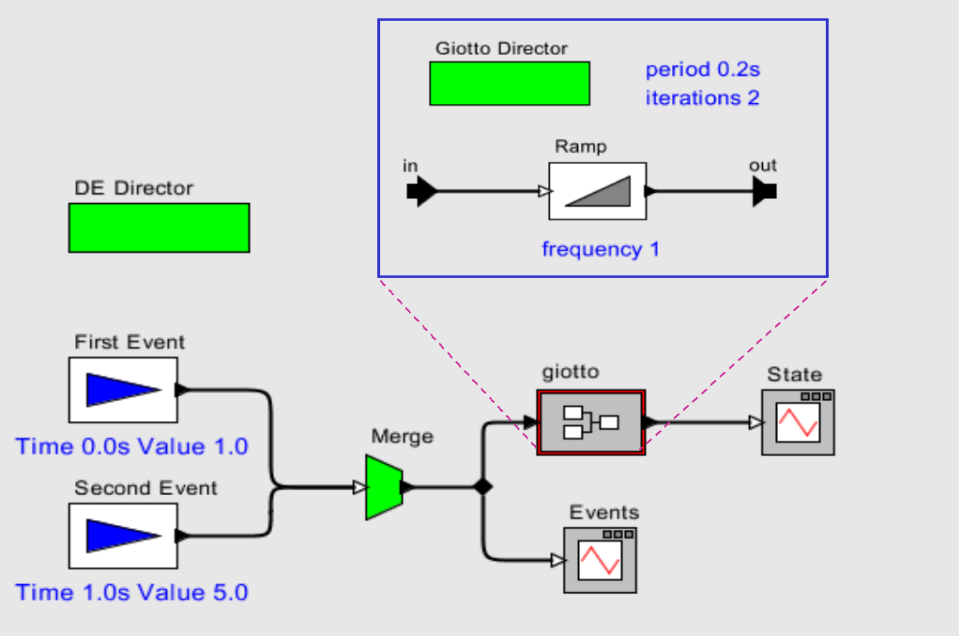


FIGURE 5.4. Giotto model embedded in DE model.

There are a few important issues:

i. The results in states plot has 0.2 sec. delay according to the Giotto semantics.

ii. For each input to the Giotto model, two outputs are generated since the value of the iterations parameter is 2.

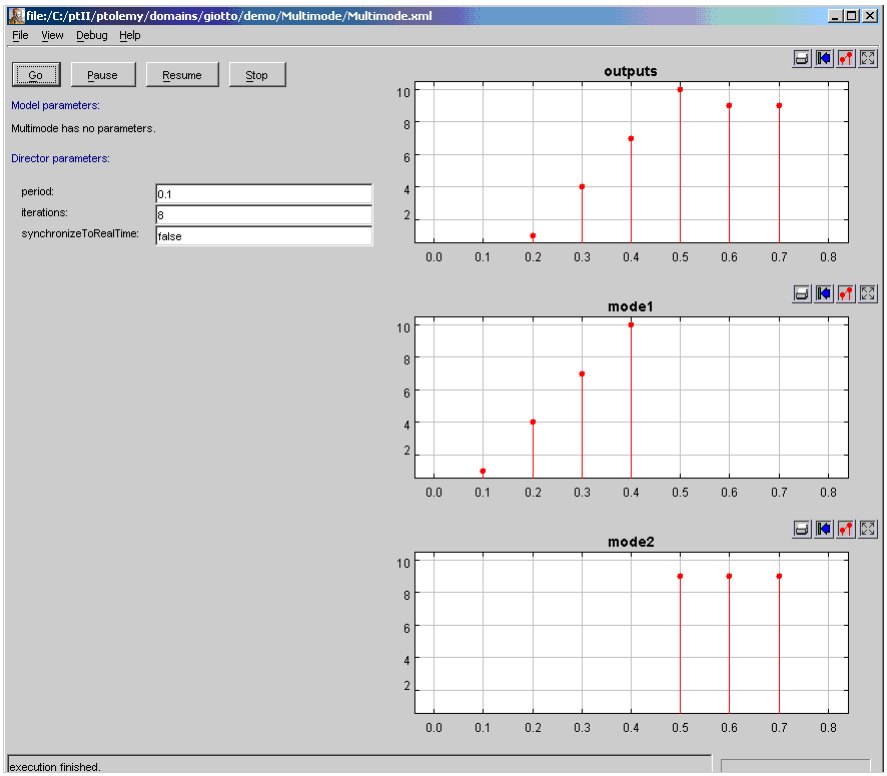


FIGURE 5.5. Simulation results of model of Figure 5.4

When a Giotto model is composed inside a CT model, the Giotto model is always invoked. So, the iterations parameter does not has effect.

5.3.2 FSM and SDF embedded inside Giotto

A Giotto model may be composed of several modes. To realize mode switching, we employed the modal model. A modal model is basically a FSM with the states which may be refined into other models of computations. The details of the modal model is in Chapter 16. In our example, the states are refined into the SDF models. The details of the SDF domain is in Chapter 15.

The model shown in Figure 5.6 can be found at $PTII/ptolemy/domains/giotto/demo/Multimode/Multimode.xml. This model is a simple implementation of mode switching where each mode has only one task, (implemented as a SDF model). The modal model has three states, init, mode1 and mode2. The default state is init and it is never reached again after the execution starts. The states mode1 and mode2 are refined into the tasks doing *addition* and *subtraction* respectively.

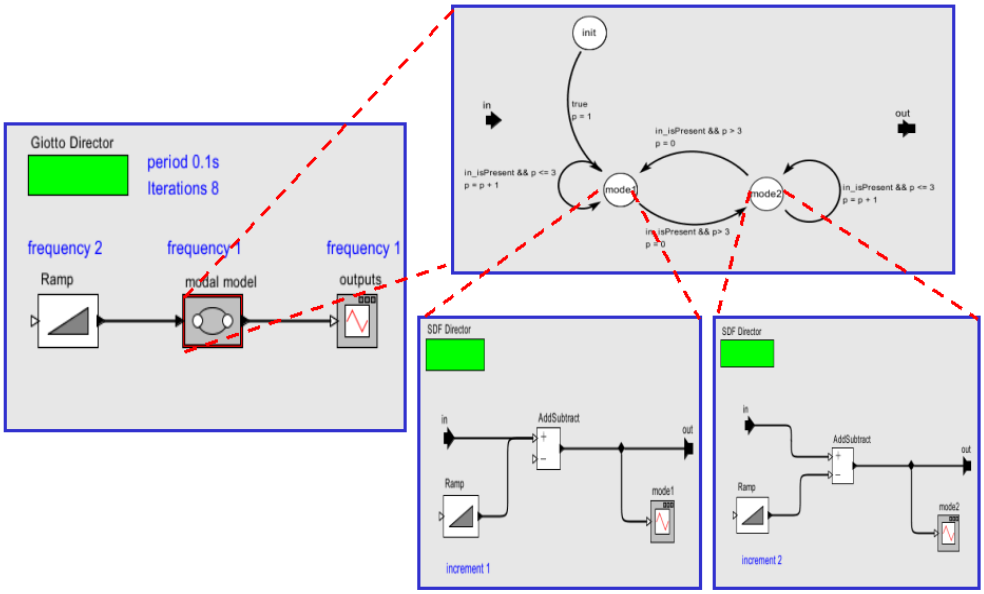


FIGURE 5.6. Modal model embedded in Giotto model.

The simulation result is shown in Figure 5.7. The *outputs* plotter resides in the Giotto model. *Mode1* plotter and *mode2* plotter reside in states of mode1 and mode2.

The *outputs* plot shows the results have 0.1 sec. delay according to the Giotto semantics. At time 0.4 sec., the *mode1* plot shows a mode switching (from mode1 to mode2) happens. However, the mode switching does not show on the outputs plot until 0.5 sec.

Note that in the *mode2* plot, the last result at 0.7 sec. does not show up in the outputs plot. The reason is that although the result of mode2 is available at 0.7 sec., it is not transferred to the outputs actor until 0.8 sec. Thus, the *outputs* plotter could not show the result until 0.8 sec., which exceeds the iterations limit.

5.4 Software structure of the Giotto Domain and implementation

The Giotto kernel package implements the Giotto model of computation. It's composed of three classes: *GiottoScheduler*, *GiottoDirector* and *GiottoReceiver*. Also, a code generation tool specially for the E-complier developed by Christoph and others is provided as *GiottoCodeGenerator*. The structure of classes is shown the Figure 5.8.

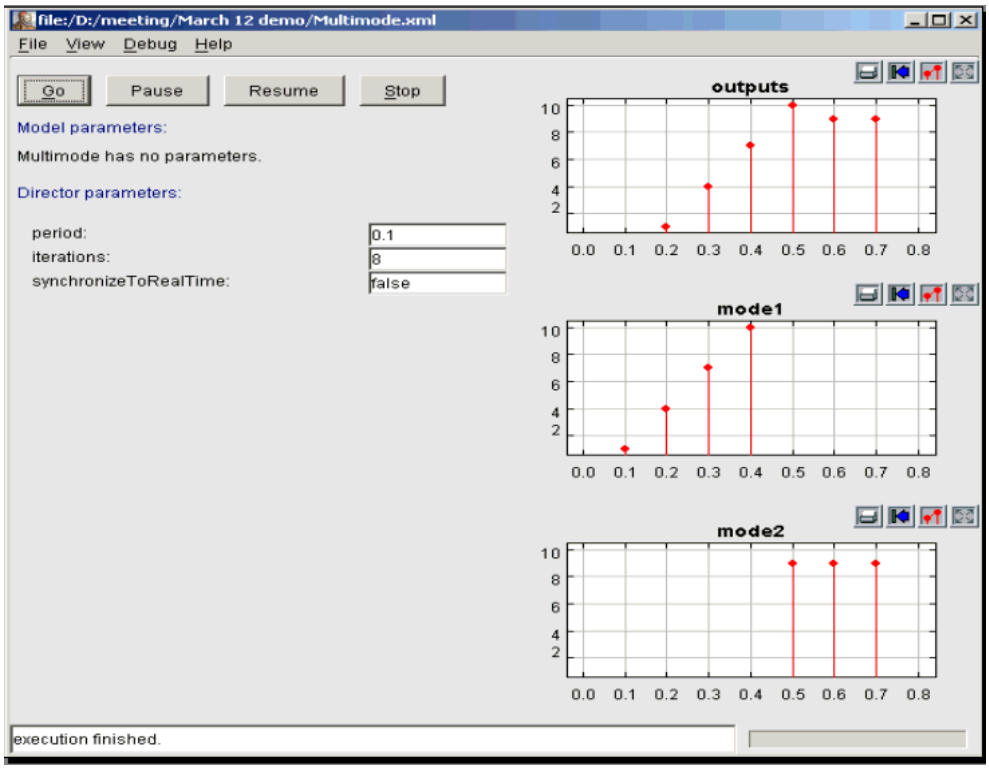


FIGURE 5.7. Simulation results for model in Figure 5.6.

5.4.1 GiottoDirector

GiottoDirector extends StaticSchedulingDirector class. It implements a model of computation according to the Giotto semantics with the help of the GiottoScheduler and the GiottoReceiver. GiottoScheduler provides a list of schedules and GiottoReceiver provides the buffered states.

There are three parameters associated with the GiottoDirector: *period*, *iterations* and *synchronizeToRealTime*. The execution phases of GiottoDirector include *initialize, prefire, fire* and *postfire*.

1. In the *initialize* phase, the director resets all the receivers and properly initializes the output ports of actors. The director also gets the list of schedules. A schedule is a list of actors to be fired at the same time. It synchronizes to the cpu time if the parameter synchronizeToRealTime is true.

2. In the *prefire* phase, the director updates the current time from upper level director if necessary. It also decides to firing or not by checking whether the current time is less than the expected execution time.

3. In the *fire* phase, the director iterates the list of schedules via index indicator *unitIndex*. Each time, the unitIndex is incremented by 1 referring to the next schedule. When it exceeds the schedule list size, it rounds back to 0. The director does two things in sequence: invoking all the actors listed in the schedule and transferring outputs of the actors after their executions. The director needs to be synchronized to real time if the parameter synchronizeToRealTime is true.

4. In the *postfire* phase, if the Giotto model is embedded, the director does not advance time by itself. Its next firing is scheduled by the executive director (in the example in Figure 5.4, the DE direc-

tor). Note that the last transfer of outputs happens after the execution of all the actors and no actors are fired. A boolean variable *transferOutputsOnly* is introduced to indicate the transfer. When the iterations requirement is first met, the director sets *transferOutputsOnly* to true and prepares for the next iteration. The postfire() method returns true. In the immediately following postfire phase, *transferOutputsOnly* is set back to false. The postfire() method returns false to terminate the model execution.

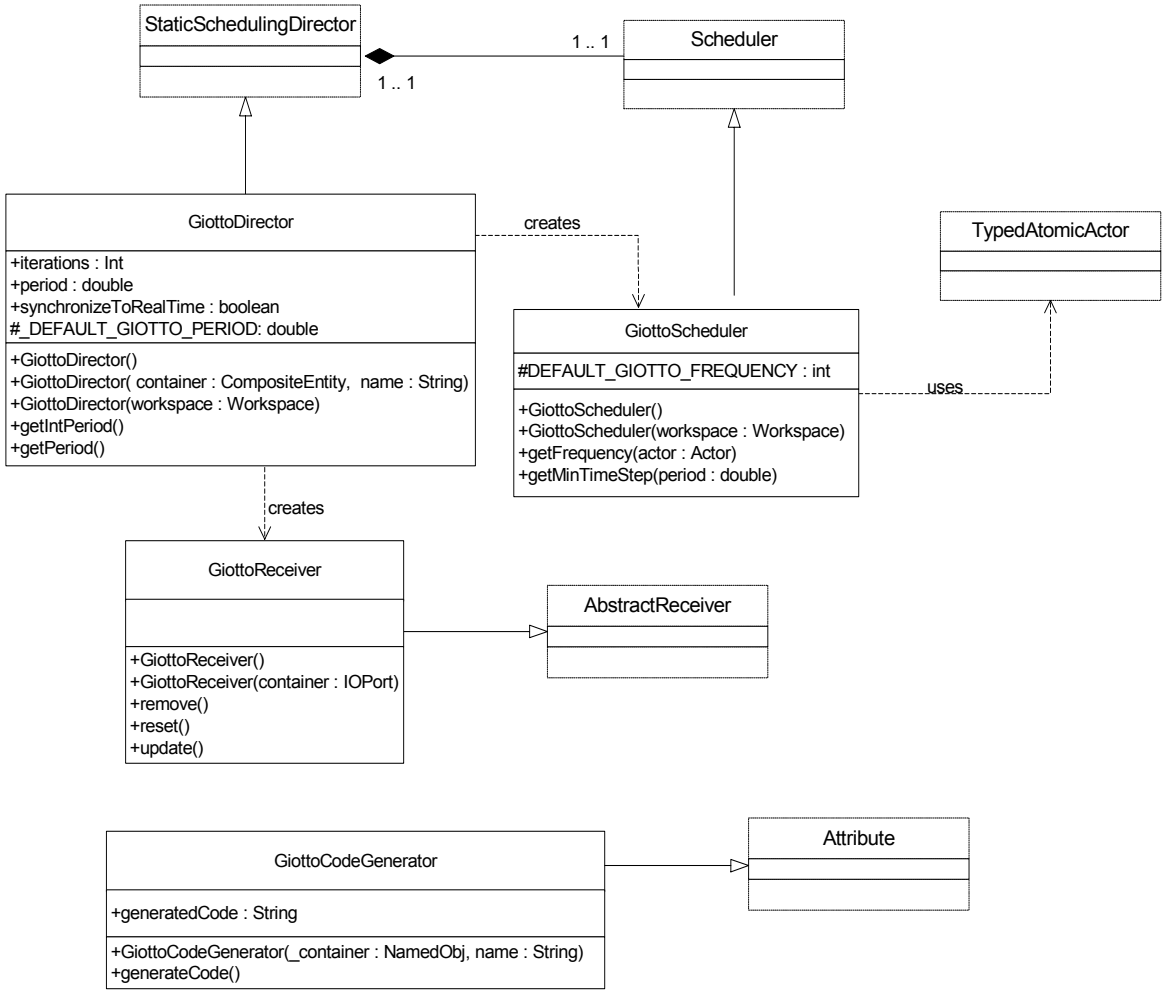


FIGURE 5.8. The static structure of the Giotto package kernel classes.

When the Giotto model is embedded inside other models, for example, the model in Figure 5.4. The Giotto director asks GiottoReceiver to call remove() instead of get(), otherwise, the *states* plotter will always be fired because the _token is not cleared.

5.4.2 GiottoScheduler

GiottoScheduler extends the Scheduler class. It is used to construct a list of schedules for the GiottoDirector. A schedule is a list of actors that will be fired by the GiottoDirector at the same time. Giot-

toScheduler provides two things for GiottoDirector: the minimum unit time increment for GiottoDirector to advance time and the list of schedules. To get schedule, use getSchedule() method from GiottoDirector.

GiottoScheduler first makes topology analysis to construct a list of the actors including the opaque composite actors and atomic actors. It also constructs an array *frequencyArray*, the elements are the frequency values associated with the actor list. With the frequencyArray, the greatest common divider (*gcd*) and the least common multiple (*lcm*) of all the frequency values are calculated. The minimum unit time increment is defined as *period / lcm*. With frequencyArray and lcm, another array: *intervalArray* is constructed to indicate when the actor to be added into schedule.

In order to compute the schedule, a simple timer: *giottoSchedulerTime* is introduced, which iterates from 0 to *lcm* with tick increment of *gcd*.

When constructing the list of schedules, there are two loops. The outer loop iterates the giottoSchedulerTime. The inner loop iterates the intervalArray. The inner loop constructs the *fireAtSameTimeSchedule*. The outer loop constructs a *schedule*, the list of the fireAtSameTimeSchedules. The Java code of schedule computation is shown in Figure 5.9.

```
Schedule schedule = new Schedule();

for (  _giottoSchedulerTime = 0; _giottoSchedulerTime < _lcm; ) {

    Schedule fireAtSameTimeSchedule = new Schedule();
    actorListIterator = actorList.listIterator();

    for (i = 0; i < actorCount; i++ ) {
        Actor actor = (Actor) actorListIterator.next();
        if ((_giottoSchedulerTime % intervalArray[i]) == 0)
                    {
                        Firing firing = new Firing();
                        firing.setActor(actor);
                        fireAtSameTimeSchedule.add(firing);
                    }
    }

    _giottoSchedulerTime += _gcd;
    schedule.add(fireAtSameTimeSchedule);
}
```

FIGURE 5.9. Schedule computation of GiottoScheduler.

5.4.3 GiottoReceiver

GiottoReceiver extends the AbstractReceiver class. The key point is that the GiottoReceiver has double buffers: *_nextToken* and *_token*. When the get() method is called, a **copy** of _token is consumed. When the put() method is called, only the _nextToken is updated. When the update() method is called, the _token is updated by _nextToken. When the remove() method is called, a copy of the _token is returned and the _token is cleared. It is the GiottoDirector that delays *update* calls to realize the Giotto semantics.

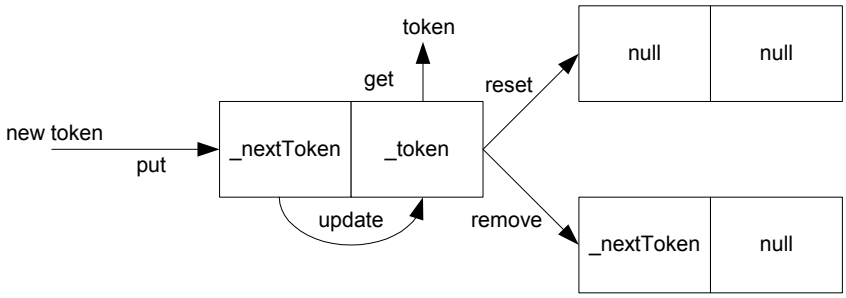


FIGURE 5.10. Working mechanism of GiottoReceiver.

The GiottoReceiver also has a reset() method. Reset is used to clear all the tokens including _nextToken and _token but returns nothing. Remove is used to return the _token and clear it but keeps _nextToken. Reset is used for initialization and remove is used for transfer of outputs to outside environment when the Giotto model is embedded inside other models.

5.4.4 GiottoCodeGenerator

GiottoCodeGenerator extends Attribute class. It is used to generate Giotto code for E-Compiler for schedulability analysis.

The current GiottoCodeGenerator works for one mode only. It iterates all the entities and treats them as tasks. From the input ports of the entities, source ports and their containers are traced. The model inputs are treated as sensors and the model outputs are treated as actuators.

The generated Giotto code usually has six parts: sensorCode, actuatorCode, outputCode, taskCode, driverCode and modeCode. The sensorCode and actuatorCode are the interfaces to the outside environment. The outputCode and driverCode describe the data dependencies. Note that for outputCode, it is illegal for an input port to have more than one source. TaskCode is the description of the computation of tasks (actors). ModeCode defines which tasks are in each mode, along with their parameters.

The example code is in Figure 5.3.

6

CSP Domain

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6.1 Introduction

The communicating sequential processes (CSP) domain in Ptolemy II models a system as a network of sequential processes that communicate by passing messages synchronously through channels. If a process is ready to send a message, it blocks until the receiving process is ready to accept the message. Similarly if a process is ready to accept a message, it blocks until the sending process is ready to send the message. This model of computation is non-deterministic as a process can be blocked waiting to send or receive on any number of channels. It is also highly concurrent.

The CSP domain is based on the model of computation (MoC) first proposed by Hoare [50][51] in 1978. In this MoC, a system is modeled as a network of processes communicate solely by passing messages through unidirectional channels. The transfer of messages between processes is via *rendezvous*, which means both the sending and receiving of messages from a channel are *blocking*: i.e. the sending or receiving process stalls until the message is transferred. Some of the notation used here is borrowed from Gregory Andrews' book on concurrent programming [7], which refers to rendezvous-based message passing as *synchronous message passing*.

Applications for the CSP domain include resource management and high level system modeling early in the design cycle. Resource management is often required when modeling embedded systems, and to further support this, a notion of time has been added to the model of computation used in the domain. This differentiates our CSP model from those more commonly encountered, which do not typically have any notion of time, although several versions of timed CSP have been proposed [48]. It might thus be more accurate to refer to the domain using our model of computation as the "Timed CSP" domain, but since it can be used with and without time, it is simply referred to as the CSP domain.

6.2 Using CSP

There are two basic issues that must be addressed when using the CSP domain:

- Unconditional vs. conditional rendezvous
- Time

6.2.1 Unconditional vs. Conditional Rendezvous

The basic communication statements send() and get() correspond to rendezvous communication in the CSP domain. Because of the domain framework, fact that a rendezvous is occurring on every communication is transparent to the actor code. However, this rendezvous is unconditional; an actor can only attempt to communicate on one port at a time. To realize the full power of the CSP domain, which allows non-deterministic rendezvous, it is necessary to write custom actors that use the conditional communication constructs in the CSPActor base class. There are three steps involved:

1) Create a ConditionalReceive or ConditionalSend branch for each guarded communication statement, depending on the communication. Pass each branch a unique integer identifier, starting from zero, when creating it.

2) Pass the branches to the chooseBranch() method in CSPActor. This method evaluates the guards, and decides which branch gets to rendezvous, performs the rendezvous and returns the identification number of the branch that succeeded. If all of the guards were false, -1 is returned.

3) Execute the statements for the guarded communication that succeeded.

A sample template for executing a conditional communication is shown in figure 6.1. This template corresponds to the CDO construct in CSP, described in section 6.3.2. In creating the ConditionalSend and ConditionalReceive branches, the first argument represents the guard. The second and third

```
boolean continueCDO = true;
while (continueCDO) {
   // step 1:
   ConditionalBranch[] branches = new ConditionalBranch[#branchesRequired];
   // Create a ConditionalReceive or a ConditionalSend for each branch
   // e.g. branches[0] = new ConditionalReceive((guard), input, 0, 0);

   // step 2:
   int result = chooseBranch(branches);

   // step 3:
   if (result == 0) {
      // execute statements associated with first branch
   } else if (result == 1) {
      // execute statements associated with second branch.
   } else if ... // continue for each branch ID

   } else if (result == -1) {
      // all guards were false so exit CDO.
      continueCDO = false;
   } else {
      // error
   }
}
```

FIGURE 6.1. Template for executing a CDO construct.

arguments represent the port and channel to send or receive the message on. The fourth argument is the identifier assigned to the branch. The choice of placing the guard in the constructor was made to keep the syntax of using guarded communication statements to the minimum, and to have the branch classes resemble the guarded communication statements they represent as closely as possible. This can give rise to the case where the Token specified in a ConditionalSend branch may not yet exist, but this has no effect because once the guard is false, the token in a ConditionalSend is never referenced.

The code for using a CIF is similar to that in figure 6.1 except that the surrounding while loop is omitted and the case when the identifier returned is -1 does nothing. At some stage the steps involved in using a CIF or a CDO may be automated using a pre-parser, but for now the user must follow the approach described above.

Figure 6.2 shows some actual code based on the template above that implements a buffer process. This process repeatedly rendezvous on its input port and its output port, buffering the data if the reading process is not yet ready for the writing process. It is worth pointing out that if most channels in a model are buffered in this way, it may be more reasonable to create the model in the PN domain which implicitly has an unbounded buffer on every channel.

6.2.2 Time

The CSP domain does not currently use the fireAt() mechanism to model time. If an actor wishes be delayed a certain amount of time during execution of the model, it must derive from CSPActor. each process in the CSP domain is able to delay itself, either for some period from the current model time or until the next occasion time deadlock is reached at the current model time. The two methods to call are delay() and waitForDeadlock(). If a process delays itself for zero time from the current time, the pro-

```
boolean guard = false;
boolean continueCDO = true;
ConditionalBranch[] branches = new ConditionalBranch[2];
while (continueCDO) {
    // step 1
    guard = (_size < depth);
    branches[0] = new ConditionalReceive(guard, input, 0, 0);
    guard = (_size > 0);
    branches[1] = new ConditionalSend(guard, output, 0, 1, _buffer[_readFrom]);

    // step 2
    int successfulBranch = chooseBranch(branches);

    // step 3
    if (successfulBranch == 0) {
        _size++;
        _buffer[_writeTo] = branches[0].getToken();
        _writeTo = ++_writeTo % depth;
    } else if (successfulBranch == 1) {
        _size--;
        _readFrom = ++_readFrom % depth;
    } else if (successfulBranch == -1) {
        // all guards false so exit CDO
        // Note this cannot happen in this case
        continueCDO = false;
    } else {
        throw new TerminateProcessException(getName() + ": " +
                "branch id returned during execution of CDO.");
    }
}
```

FIGURE 6.2. Code used to implement the buffer process described in figure 6.1.

cess will continue immediately. Thus delay(0.0) is not equivalent to waitForDeadlock()

As far as each process is concerned, time can only increase while it is blocked waiting to rendezvous or when it is delayed. A process can be aware of the current model time, but it should only ever affect the model time by delaying its execution, thus forcing time to advance. The method setCurrentTime() should never be called from a process. However, if no processes are delayed, it is possible to set the model time by calling the setCurrentTime() method of the director. However, this method is present only for composing CSP with other domains.

By default every model in the CSP domain is timed. To use CSP without a notion of time, simply do not use the delay() method. The infrastructure supporting time does not affect the model execution if this method is not used. For more information about the semantics of Timed CSP models, see section 6.3.4

6.3 Properties of the CSP Domain

At the core of CSP communication semantics are two fundamental ideas. First is the notion of atomic communication and second is the notion of nondeterministic choice. It is worth mentioning a related model of computation known as the calculus of communicating systems (CCS) that was independently developed by Robin Milner in 1980 [90]. The communication semantics of CSP are identical to those of CCS.

6.3.1 Atomic Communication: Rendezvous

Atomic communication is carried out via rendezvous and implies that the sending and receiving of a message occur simultaneously. During rendezvous both the sending and receiving processes block until the other side is ready to communicate; the act of sending and receiving is indistinguishable activities since one can not happen without the other. A real world analogy to rendezvous can be found in telephone communications (without answering machines). Both the caller and callee must be simultaneously present for a phone conversation to occur. Figure 6.3 shows the case where one process is ready to send before the other process is ready to receive. The communication of information in this way can be viewed as a distributed assignment statement.

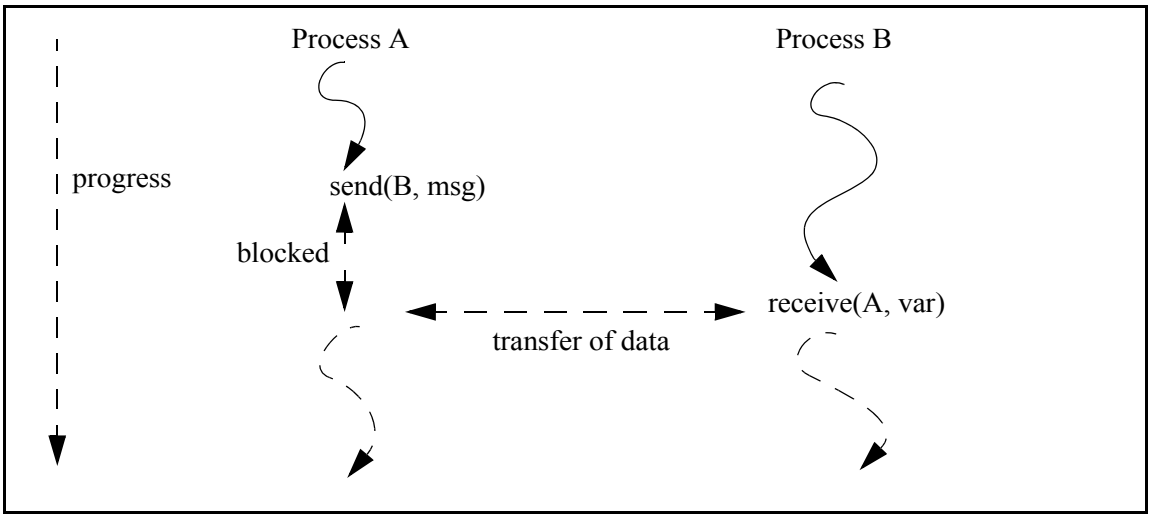

FIGURE 6.3. Illustrating how processes block waiting to rendezvous

The sending process places some data in the message that it wants to send. The receiving process assigns the data in the message to a local variable. Of course, the receiving process may decide to ignore the contents of the message and only concern itself with the fact that a message arrived.

6.3.2 Choice: Nondeterministic Rendezvous

Nondeterministic choice provides processes with the ability to randomly select between a set of possible atomic communications. We refer to this ability as nondeterministic rendezvous and herein lies much of the expressiveness of the CSP model of computation. The CSP domain implements nondeterministic rendezvous via *guarded communication statements.* A guarded communication statement has the form

```
guard; communication => statements;
```

The *guard* is only allowed to reference local variables, and its evaluation cannot change the state of the process. For example it is not allowed to assign to variables, only reference them. The *communication* must be a simple send or receive, i.e. another conditional communication statement cannot be placed here. *Statements* can contain any arbitrary sequence of statements, including more conditional communications.

If the guard is false, then the communication is not attempted and the statements are not executed. If the guard is true, then the communication is attempted, and if it succeeds, the following statements are executed. The guard may be omitted, in which case it is assumed to be true.

There are two conditional communication constructs built upon the guarded communication statements: **CIF** and **CDO**. These are analogous to the *if* and *while* statements in most programming languages. They should be read as “conditional if” and “conditional do”. Note that each guarded communication statement represents one *branch* of the CIF or CDO. The communication statement in each branch can be either a send or a receive, and they can be mixed freely.

CIF: The form of a CIF is

```
CIF {
     G1;C1 => S1;
[]
     G2;C2 => S2;
[]
     ...
}
```

For each branch in the CIF, the guard (*G1*, *G2*,...) is evaluated. If it is true (or absent, which implies true), then the associated communication statement is enabled. If one or more branch is enabled, then the entire construct blocks until one of the communications succeeds. If more than one branch is enabled, the choice of which enabled branch succeeds with its communication is made nondeterministically. Once the successful communication is carried out, the associated statements are executed and the process continues. If all of the guards are false, then the process continues executing statements after the end of the CIF.

It is important to note that, although this construct is analogous to the common *if* programming construct, its behavior is very different. In particular, all guards of the branches are evaluated concur-

rently, and the choice of which one succeeds does not depend on its position in the construct. The notation "[]" is used to hint at the parallelism in the evaluation of the guards. In a common *if*, the branches are evaluated sequentially and the first branch that is evaluated to true is executed. The CIF construct also depends on the semantics of the communication between processes, and can thus stall the progress of the thread if none of the enabled branches is able to rendezvous.

CDO: The form of the CDO is

```
CDO {
     G1;C1 => S1;
[]
     G2;C2 => S2;
[]
     ...
}
```

The behavior of the CDO is similar to the CIF in that for each branch the guard is evaluated and the choice of which enabled communication to make is taken non-deterministically. However, the CDO repeats the process of evaluating and executing the branches until *all* the guards return false. When this happens the process continues executing statements after the CDO construct.

An example use of a CDO is in a buffer process which can both accept and send messages, but has to be ready to do both at any stage. The code for this would look similar to that in figure 6.4. Note that in this case both guards can never be simultaneously false so this process will execute the CDO forever.

6.3.3 Deadlock

A deadlock situation is one in which none of the processes can make progress: they are all either blocked trying to rendezvous or they are delayed (see the next section). Thus, two types of deadlock can be distinguished:

real deadlock - all active processes are blocked trying to communicate

time deadlock - all active processes are either blocked trying to communicate or are delayed, and at least one processes is delayed.

6.3.4 Time

In the CSP domain, *time* is centralized. That is, all processes in a model share the same time, referred to as the *current model time*. Each process can only choose to *delay* itself for some period relative to the current model time, or a process can wait for time deadlock to occur at the current model time. In both cases, a process is said to be *delayed*.

When a process delays itself for some length of time from the current model time, it is suspended

```
CDO {
    (room in buffer?); receive(input, beginningOfBuffer) => update pointer to beginning of buffer;
[]
    (messages in buffer?); send(output, endOfBuffer) => update pointer to end of buffer;
}
```

FIGURE 6.4. Example of how a CDO might be used in a buffer

until time has sufficiently advanced, at which stage it wakes up and continues. If the process delays itself for zero time, this will have no effect and the process will continue executing.

A process can also choose to delay its execution until the next occasion a time deadlock is reached. The process resumes at the same model time at which it delayed, and this is useful as a model can have several sequences of actions at the same model time. The next occasion time deadlock is reached, any processes delayed in this manner will continue, and time will not be advanced. An example of using time in this manner can be found in section 6.5.2.

Time may be *advanced* when all the processes are delayed or are blocked trying to rendezvous, and at least one process is delayed. If one or more processes are delaying until a time deadlock occurs, these processes are woken up and time is not advanced. Otherwise, the current model time is advanced just enough to wake up at least one process. Note that there is a semantic difference between a process delaying for zero time, which will have no effect, and a process delaying until the next occasion a time deadlock is reached.

Note also that time, as perceived by a single process, cannot change during its normal execution; only at rendezvous points or when the process delays can time change. A process can be aware of the centralized time, but it cannot influence the current model time except by delaying itself. The choice for modeling time was in part influenced by Pamela [36], a run time library that is used to model parallel programs.

6.3.5 Differences from Original CSP Model as Proposed by Hoare

The model of computation used by the CSP domain differs from the original CSP [50] model in two ways. First, a notion of time has been added. The original proposal had no notion of time, although there have been several proposals for timed CSP [48]. Second, as mentioned in section 6.3.2, it is possible to use both send and receive in guarded communication statements. The original model only allowed receives to appear in these statements, though Hoare subsequently extended their scope to allow both communication primitives [51].

One final thing to note is that in much of the CSP literature, send is denoted using a "!", pronounced "bang", and receive is denoted using a "?", pronounced "query". This syntax was what was used in the original CSP paper by Hoare. For example, the languages Occam [19] and Lotos [29] both follow this syntax. In the CSP domain in Ptolemy II we use *send* and *get*, the choice of which is influenced by the desire to maintain uniformity of syntax across domains in Ptolemy II that use message passing. This supports the heterogeneity principle in Ptolemy II which enables the construction and inter-operability of executable models that are built under a variety of models of computation. Similarly, the notation used in the CSP domain for conditional communication constructs differs from that commonly found in the CSP literature.

6.4 The CSP Software Architecture

6.4.1 Class Structure

In a CSP model, the director is an instance of *CSPDirector*. Since the model is controlled by a CSPDirector, all the receivers in the ports are *CSPReceivers*. The combination of the CSPDirector and CSPReceivers in the ports gives a model CSP semantics. The CSP domain associates each channel with exactly one receiver, located at the receiving end of the channel. Thus any process that sends or receives to any channel will rendezvous at a CSPReceiver. Figure 6.5 shows the static structure dia-

gram of the five main classes in the CSP kernel, and a few of their associations. These are the classes that provide all the infrastructure needed for a CSP model.

CSPDirector: This gives a model CSP semantics. It takes care of starting all the processes and controls/responds to both real and time deadlocks. It also maintains and advances the model time when necessary.

CSPReceiver: This ensures that communication of messages between processes is via rendezvous.

CSPActor: This adds the notion of time and the ability to perform conditional communication.

ConditionalReceive, ConditionalSend: This is used to construct the guarded communication statements necessary for the conditional communication constructs.

6.4.2 Starting the model

The director creates a thread for each actor under its control in its initialize() method. It also invokes the initialize() method on each actor at this time. The director starts the threads in its prefire() method, and detects and responds to deadlocks in its fire() method. The thread for each actor is an instance of ProcessThread, which invokes the prefire(), fire() and postfire() methods for the actor until it finishes or is terminated. It then invokes the wrapup() method and the thread dies.

Figure 6.7 shows the code executed by the ProcessThread class. Note that it makes no assumption about the actor it is executing, so it can execute any domain-polymorphic actor as well as CSP domain-specific actors. In fact, any other domain actor that does not rely on the specifics of its parent domain can be executed in the CSP domain by the ProcessThread.

6.4.3 Detecting deadlocks:

For deadlock detection, the director maintains three counts:

- the number of *active* processes which are threads that have started but have not yet finished
- the number of *blocked* processes which is the number of processes that are blocked waiting to rendezvous, and

```
director.initialize() =>
   create a thread for each actor
   update count of active processes with the director
   call initialize() on each actor

director.prefire() => start the process threads =>
   calls actor.prefire()
   calls actor.fire()
   calls actor.postfire()
   repeat.

director.fire() => handle deadlocks until a real deadlock occurs.

director.postfire() =>
   return a boolean indicating if the execution of the model should continue for another iteration

director.wrapup() => terminate all the processes =>
   calls actor.wrapup()
   decrease the count of active processes with the director
```

FIGURE 6.6. Sequence of steps involved in setting up and controlling the model.

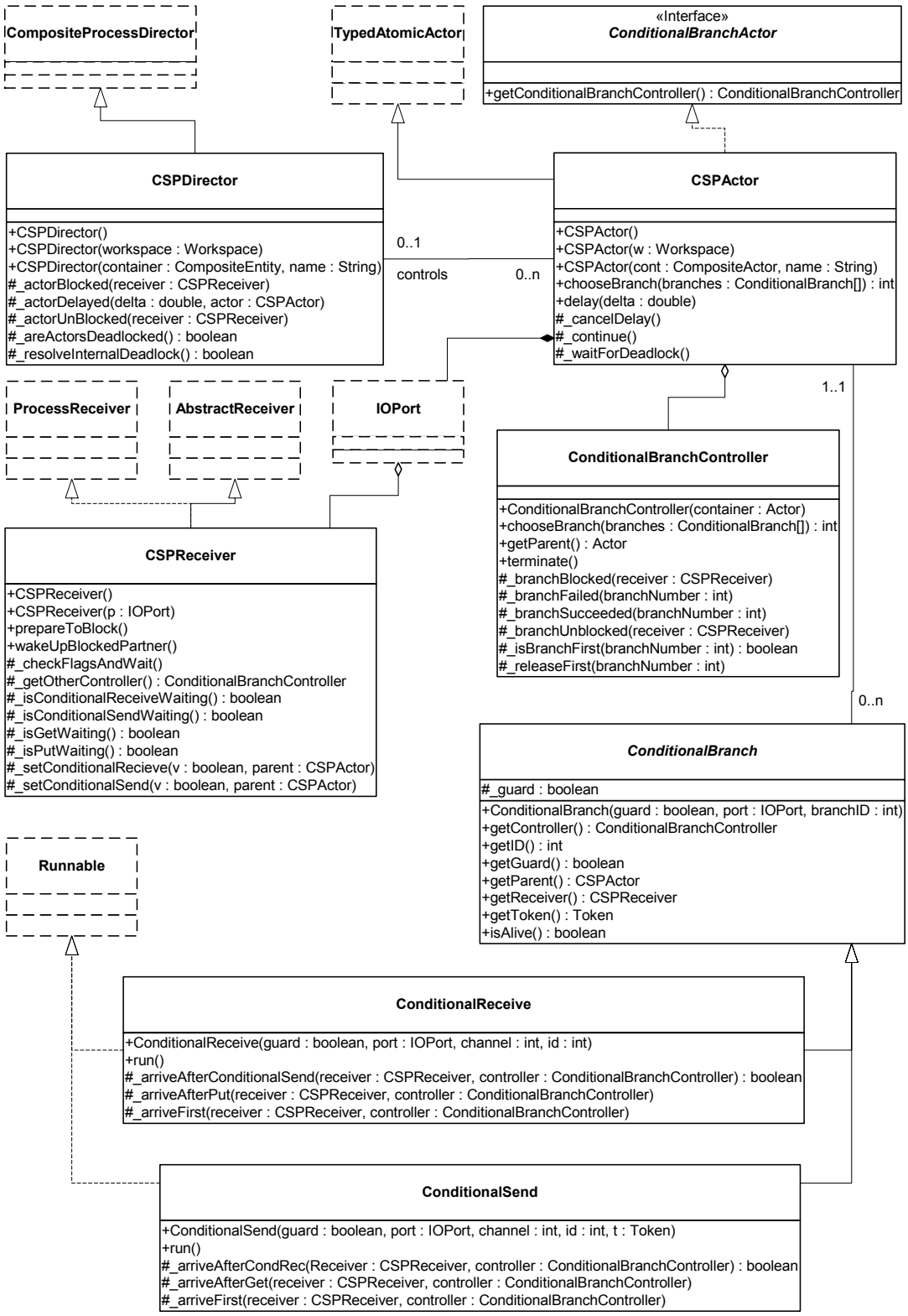

FIGURE 6.5. Static structure diagram for classes in the CSP kernel.

- the number of *delayed* processes, which is the number of processes waiting for time to advance plus the number of processes waiting for time deadlock to occur at the current model time.

When the number of blocked processes equals the number of active processes, then real deadlock has occurred and the fire method of the director returns. When the number of blocked plus the number of delayed processes equals the number of active processes, and at least one process is delayed, then time deadlock has occurred. If at least one process is delayed waiting for time deadlock to occur at the current model time, then the director wakes up all such processes and does not advance time. Otherwise the director looks at its list of processes waiting for time to advance, chooses the earliest one and advances time sufficiently to wake it up. It also wakes up any other processes due to be awakened at the new time. The director checks for deadlock each occasion a process blocks, delays or dies.

For the director to work correctly, these three counts need to be accurate at all stages of the model execution, so when they are updated becomes important. Keeping the active count accurate is relatively simple; the director increases it when it starts the thread, and decreases it when the thread dies. Likewise the count of delayed processes is straightforward; when a process delays, it increases the count of delayed processes, and the director keeps track of when to wake it up. The count is decreased when a delayed process resumes.

However, due to the conditional communication constructs, keeping the blocked count accurate requires a little more effort. For a basic send or receive, a process is registered as being blocked when it arrives at the rendezvous point before the matching communication. The blocked count is then decreased by one when the corresponding communication arrives. However what happens when an actor is carrying out a conditional communication construct? In this case the process keeps track of all of the branches for which the guards were true, and when all of those are blocked trying to rendezvous, it registers the process as being blocked. When one of the branches succeeds with a rendezvous, the process is registered as being unblocked.

```
public void run() {
    try {
        boolean iterate = true;
        while (iterate) {
            // container is checked for null to detect the termination
            // of the actor.
            iterate = false;
            if ((Entity)_actor).getContainer() != null && _actor.prefire()) {
                _actor.fire();
                iterate = _actor.postfire();
            }
        }
    } catch (TerminateProcessException t) {
        // Process was terminated early
    } catch (IllegalActionException e) {
        _manager.fireExecutionError(e);
    } finally {
        try {
            _actor.wrapup();
        } catch (IllegalActionExeption e) {
            _manager.fireExecutionError(e);
        }
        _director.decreaseActiveCount();
    }
}
```

FIGURE 6.7. Code executed by ProcessThread.run().

6.4.4 Terminating the model

A process can finish in one of two ways: either by returning false in its prefire() or postfire() methods, in which case it is said to have finished *normally*, or by being terminated *early* by a TerminateProcessException. For example, if a source process is intended to send ten tokens and then finish, it would exit its fire() method after sending the tenth token, and return false in its postfire() method. This causes the ProcessThread, see figure 6.7, representing the process, to exit the while loop and execute the finally clause. The finally clause calls wrapup() on the actor it represents, decreases the count of active processes in the director, and the thread representing the process dies.

A TerminateProcessException is thrown whenever a process tries to communicate via a channel whose receiver has its *finished* flag set to true. When a TerminateProcessException is caught in ProcessThread, the finally clause is also executed and the thread representing the process dies.

To terminate the model, the director sets the *finished* flag in each receiver. The next occasion a process tries to send to or receive from the channel associated with that receiver, a TerminateProcessException is thrown. This mechanism can also be used in a selective fashion to terminate early any processes that communicate via a particular channel. When the director controlling the execution of the model detects real deadlock, it returns from its fire() method. In the absence of hierarchy, this causes the wrapup() method of the director to be invoked. It is the wrapup() method of the director that sets the finished flag in each receiver. Note that the TerminateProcessException is a runtime exception so it does not need to be declared as being thrown.

There is also the option of abruptly terminating all the processes in the model by calling terminate() on the director. This method differs from the approach described in the previous paragraph in that it stops all the threads immediately and does not give them a chance to update the model state. After calling this method, the state of the model is unknown and so the model should be recreated after calling this method. This method is only intended for situations when the execution of the model has obviously gone wrong, and for it to finish normally would either take too long or could not happen. It should rarely be called.

6.4.5 Pausing/Resuming the Model

Pausing and resuming a model does not affect the outcome of a particular execution of the model, only the rate of progress. The execution of a model can be paused at any stage by calling the pause() method on the director. This method is blocking, and will only return when the model execution has been successfully paused. To pause the execution of a model, the director sets a *paused* flag in every receiver, and the next occasion a process tries to send to or receive from the channel associated with that receiver, it is paused. The whole model is paused when all the active processes are delayed, paused or blocked. To resume the model, the resume() method can similarly be called on the director This method resets the paused flag in every receiver and wakes up every process waiting on a receiver lock. If a process was paused, it sees that it is no longer paused and continues. The ability to pause and resume the execution of a model is intended primarily for user interface control.

6.5 Example CSP Applications

Several example applications have been developed which serve to illustrate the modeling capabilities of the CSP model of computation in Ptolemy II. Each demonstration incorporates several features of CSP and the general Ptolemy II framework. The applications are described here, but not the code. See the directory $PTII/ptolemy/domains/csp/demo for the code.

The first demonstration, *dining philosophers*, serves as a natural example of core CSP communication semantics. This demonstration models nondeterministic resource contention, e.g., five philosophers randomly accessing chopstick resources. Nondeterministic rendezvous serves as a natural modeling tool for this example. The second example, *hardware bus contention*, models deterministic resource contention in the context of time. As will be shown, the determinacy of this demonstration constrains the natural nondeterminacy of the CSP semantics and results in difficulties. Fortunately these difficulties can be smoothly circumvented by the timing model that has been integrated into the CSP domain.

6.5.1 Dining Philosophers

Nondeterministic Resource Contention. This implementation of the dining philosophers problem illustrates both time and conditional communication in the CSP domain. Five philosophers are seated at a table with a large bowl of food in the middle. Between each pair of philosophers is one chopstick, and to eat, a philosopher needs both the chopsticks beside him. Each philosopher spends his life in the following cycle: thinks for a while, gets hungry, picks up one of the chopsticks beside him, then the other, eats for a while and puts the chopsticks down on the table again. If a philosopher tries to grab a chopstick but it is already being used by another philosopher, then the philosopher waits until that chopstick becomes available. This implies that no neighboring philosophers can eat at the same time and at most two philosophers can eat at a time.

The Dining Philosophers problem was first proposed by Edsger W. Dijkstra in 1965. It is a classic concurrent programming problem that illustrates the two basic properties of concurrent programming:

Liveness. How can we design the program to avoid deadlock, where none of the philosophers can make progress because each is waiting for someone else to do something?

Fairness. How can we design the program to avoid starvation, where one of the philosophers could make progress but does not because others always go first?

This implementation uses an algorithm that lets each philosopher randomly chose which chopstick to pick up first (via a CDO), and all philosophers eat and think at the same rates. Each philosopher and each chopstick is represented by a separate process. Each chopstick has to be ready to be used by either philosopher beside it at any time, hence the use of a CDO. After it is grabbed, it blocks waiting for a message from the philosopher that is using it. After a philosopher grabs both the chopsticks next to him, he eats for a random time. This is represented by calling delay() with the random interval to eat for. The same approach is used when a philosopher is thinking. Note that because messages are passed by rendezvous, the blocking of a philosopher when it cannot obtain a chopstick is obtained for free.

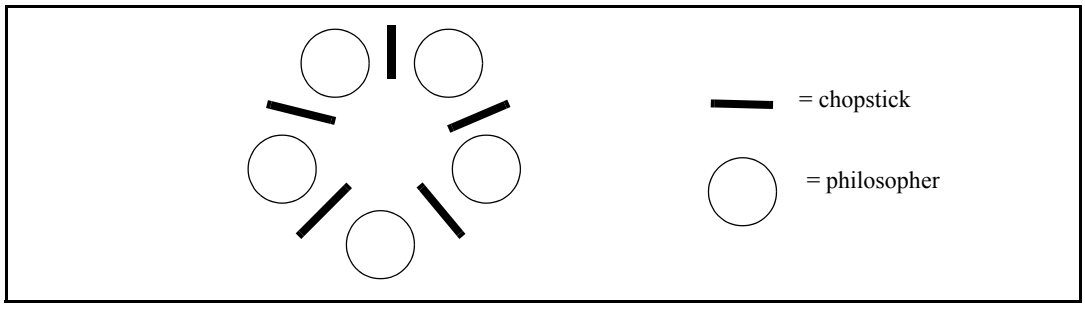

FIGURE 6.8. Illustration of the dining philosophers problem.

This algorithm is fair, as any time a chopstick is not being used, and both philosophers try to use it, they both have an equal chance of succeeding. However this algorithm does not guarantee the absence of deadlock, and if it is let run long enough this will eventually occur. The probability that deadlock occurs sooner increases as the thinking times are decreased relative to the eating times.

6.5.2 Hardware Bus Contention

Deterministic Resource Contention. This demonstration consists of a controller, *N* processors and a memory block, as shown in Figure 6.9. At randomly selected points in time, each processor requests permission from the controller to access the memory block. The processors each have priorities associated with them and in cases where there is a simultaneous memory access request, the controller grants permission to the processor with the highest priority. Due to the atomic nature of rendezvous, it is impossible for the controller to check priorities of incoming requests at the same time that requests are occurring. To overcome this difficulty, an alarm is employed. The alarm is started by the controller immediately following the first request for memory access at a given instant in time. It is awakened when a delay block occurs to indicate to the controller that no more memory requests will occur at the given point in time. Hence, the alarm uses CSP's notion of delay blocking to make deterministic an inherently non-deterministic activity.

6.6 Technical Details

6.6.1 Rendezvous Algorithm

In CSP, the locking point for all communication between processes is the receiver. Any occasion a process wishes to send or receive, it must first acquire the lock for the receiver associated with the channel it is communicating over. Two key facts to keep in mind when reading the following algorithms are that each channel has exactly one receiver associated with it and that at most one process can be trying to send to (or receive from) a channel at any stage. The constraint that each channel can have at most one process trying to send to (or receive from) a channel at any stage is not currently enforced, but an exception will be thrown if such a model is not constructed.

The rendezvous algorithm is *entirely symmetric* for the put() and the get(), except for the direction the token is transferred. This helps reduce the deadlock situations that could arise and also makes the interaction between processes more understandable and easier to explain. The algorithm controlling how a get() proceeds is shown in figure 6.10. The algorithm for a put() is exactly the same except that

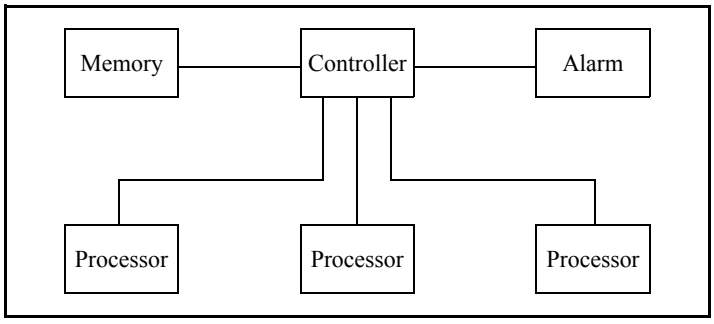

FIGURE 6.9. Illustration of the Hardware Bus Contention example.

put and get are swapped everywhere. Thus it suffices to explain what happens when a get() arrives at a receiver, i.e. when a process tries to receive from the channel associated with the receiver.

When a get() arrives at a receiver, a put() is either already waiting to rendezvous or it is not. Both the get() and put() methods are entirely synchronized on the receiver so they cannot happen simultaneously (only one thread can possess a lock at any given time). Without loss of generality assume a get() arrives before a put(). The rendezvous mechanism is basically three steps: a get() arrives, a put() arrives, the rendezvous completes.

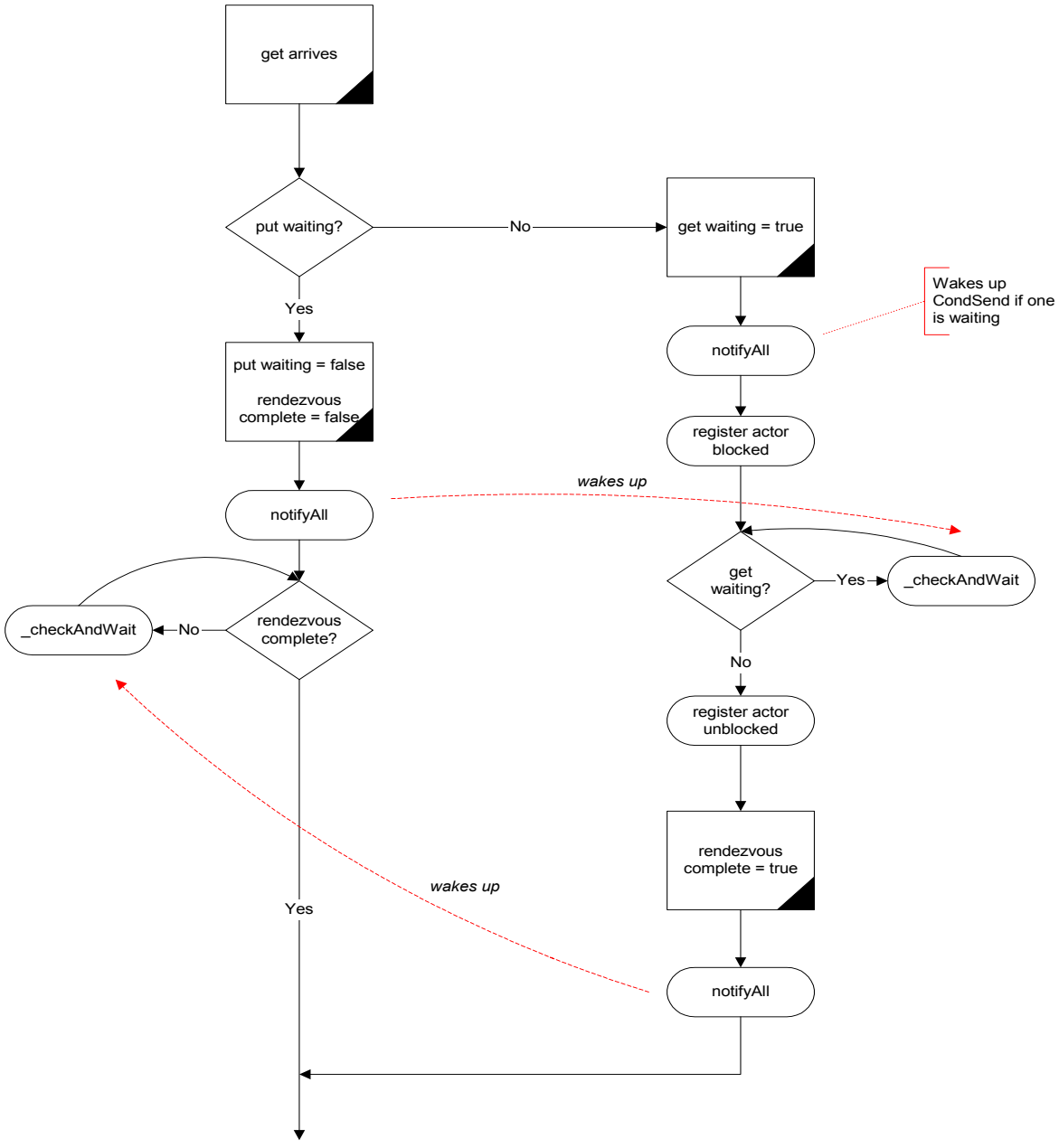

FIGURE 6.10. Rendezvous algorithm.

(1) When the get() arrives, it sees that it is first and sets a flag saying a get is waiting. It then waits on the receiver lock while the flag is still true,

(2) When a put() arrives, it sets the *getWaiting* flag to false, wakes up any threads waiting on the receiver (including the get), sets the *rendezvousComplete* flag to false and then waits on the receiver while the *rendezvousComplete* flag is false,

(3) The thread executing the get() wakes up, sees that a put() has arrived, sets the *rendezvousComplete* flag to true, wakes up any threads waiting on the receiver, and returns thus releasing the lock. The thread executing the put() then wakes up, acquires the receiver lock, sees that the rendezvous is complete and returns.

Following the rendezvous, the state of the receiver is exactly the same as before the rendezvous arrived, and it is ready to mediate another rendezvous. It is worth noting that the final step, of making sure the second communication to arrive does not return until the rendezvous is complete, is necessary to ensure that the correct token gets transferred. Consider the case again when a get() arrives first, except now the put() returns immediately if a get() is already waiting. A put() arrives, places a token in the receiver, sets the get waiting flag to false and returns. Now suppose another put() arrives before the get() wakes up, which will happen if the thread the put() is in wins the race to obtain the lock on the receiver. Then the second put() places a new token in the receiver and sets the put waiting flag to true. Then the get() wakes up, and returns with the wrong token! This is known as a *race condition*, which will lead to unintended behavior in the model. This situation is avoided by our design.

6.6.2 Conditional Communication Algorithm

There are two steps involved in executing a CIF or a CDO: first deciding which enabled branch succeeds, then carrying out the rendezvous.

Built on top of rendezvous:
When a conditional construct has more than one enabled branch (guard is true or absent), a new thread is spawned for each enabled branch. The job of the chooseBranch() method is to control these threads and to determine which branch should be allowed to successfully rendezvous. These threads and the mechanism controlling them are entirely separate from the rendezvous mechanism described in section 6.6.1, with the exception of one special case, which is described in section 6.6.3. Thus the conditional mechanism can be viewed as being built on top of basic rendezvous: conditional communication knows about and needs basic rendezvous, but the opposite is not true. Again this is a design decision which leads to making the interaction between threads easier to understand and is less prone to deadlock as there are fewer interaction possibilities to consider.

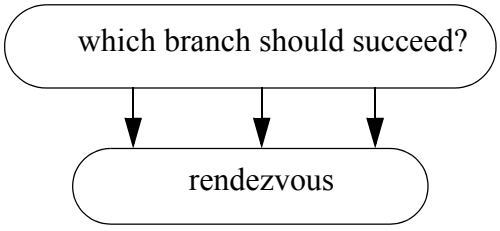

FIGURE 6.11. Conceptual view of how conditional communication is built on top of rendezvous.

Choosing which branch succeeds.
The manner in which the choice of which branch can rendezvous is worth explaining. The chooseBranch() method in CSPActor takes an array of branches as an argument. If all of the guards are false, it returns -1, which indicates that all the branches failed. If exactly one of the guards is true, it performs the rendezvous directly and returns the identification number of the successful branch. The interesting case is when more than one guard is true. In this case, it creates and starts a new thread for each branch whose guard is true. It then waits, on an internal lock, for one branch to succeed. At that point it gets woken up, sets a finished flag in the remaining branches and waits for them to fail. When all the threads representing the branches are finished, it returns the identification number of the successful branch. This approach is designed to ensure that exactly one of the branches created successfully performs a rendezvous.

Algorithm used by each branch:
Similar to the approach followed for rendezvous, the algorithm by which a thread representing a branch determines whether or not it can proceed is entirely *symmetrical* for a ConditionalSend and a ConditionalReceive. The algorithm followed by a ConditionalReceive is shown figure 6.12. Again the locking point is the receiver, and all code concerned with the communication is synchronized on the receiver. The receiver is also where all necessary flags are stored.

Consider three cases.

(1) a conditionalReceive arrives and a put is waiting.

In this case, the branch checks if it is the first branch to be ready to rendezvous, and if so, it is goes ahead and executes a get. If it is not the first, it waits on the receiver. When it wakes up, it checks if it is still alive. If it is not, it registers that it has failed and dies. If it is still alive, it starts again by trying to be the first branch to rendezvous. Note that a put cannot disappear.

(2) a conditionalReceive arrives and a conditionalSend is waiting

When both sides are conditional branches, it is up to the branch that arrives second to check whether the rendezvous can proceed. If both branches are the first to try to rendezvous, the conditionalReceive executes a get(), notifies its parent that it succeeded, issues a notifyAll() on the receiver and dies. If not, it checks whether it has been terminated by chooseBranch(). If it has, it registers with chooseBranch() that it has failed and dies. If it has not, it returns to the start of the algorithm and tries again. This is because a ConditionalSend could disappear. Note that the parent of the first branch to arrive at the receiver needs to be stored for the purpose of checking if both branches are the first to arrive.

This part of the algorithm is somewhat subtle. When the second conditional branch arrives at the rendezvous point it checks that *both* sides are the first to try to rendezvous for their respective processes. If so, then the conditionalReceive executes a get(), so that the conditionalSend is never aware that a conditionalReceive arrived: it only sees the get().

(3) a conditionalReceive arrives first.

It sets a flag in the receiver that it is waiting, then waits on the receiver. When it wakes up, it checks whether it has been killed by chooseBranch. If it has, it registers with chooseBranch that it has failed and dies. Otherwise it checks if a put is waiting. It only needs to check if a put is waiting because if a conditionalSend arrived, it would have behaved as in case (2) above. If a put is waiting, the branch checks if it is the first branch to be ready to rendezvous, and if so it is goes ahead

and executes a get. If it is not the first, it waits on the receiver and tries again.

6.6.3 Modification of Rendezvous Algorithm

Consider the case when a conditional send arrives before a get. If all the branches in the conditional communication that the conditional send is a part of are blocked, then the process will register itself as blocked with the director. Then the get comes along, and even though a conditional send is waiting, it too would register itself as blocked. This leads to one too many processes being registered as blocked, which could lead to premature deadlock detection.

To avoid this, it is necessary to modify the algorithm used for rendezvous slightly. The change to

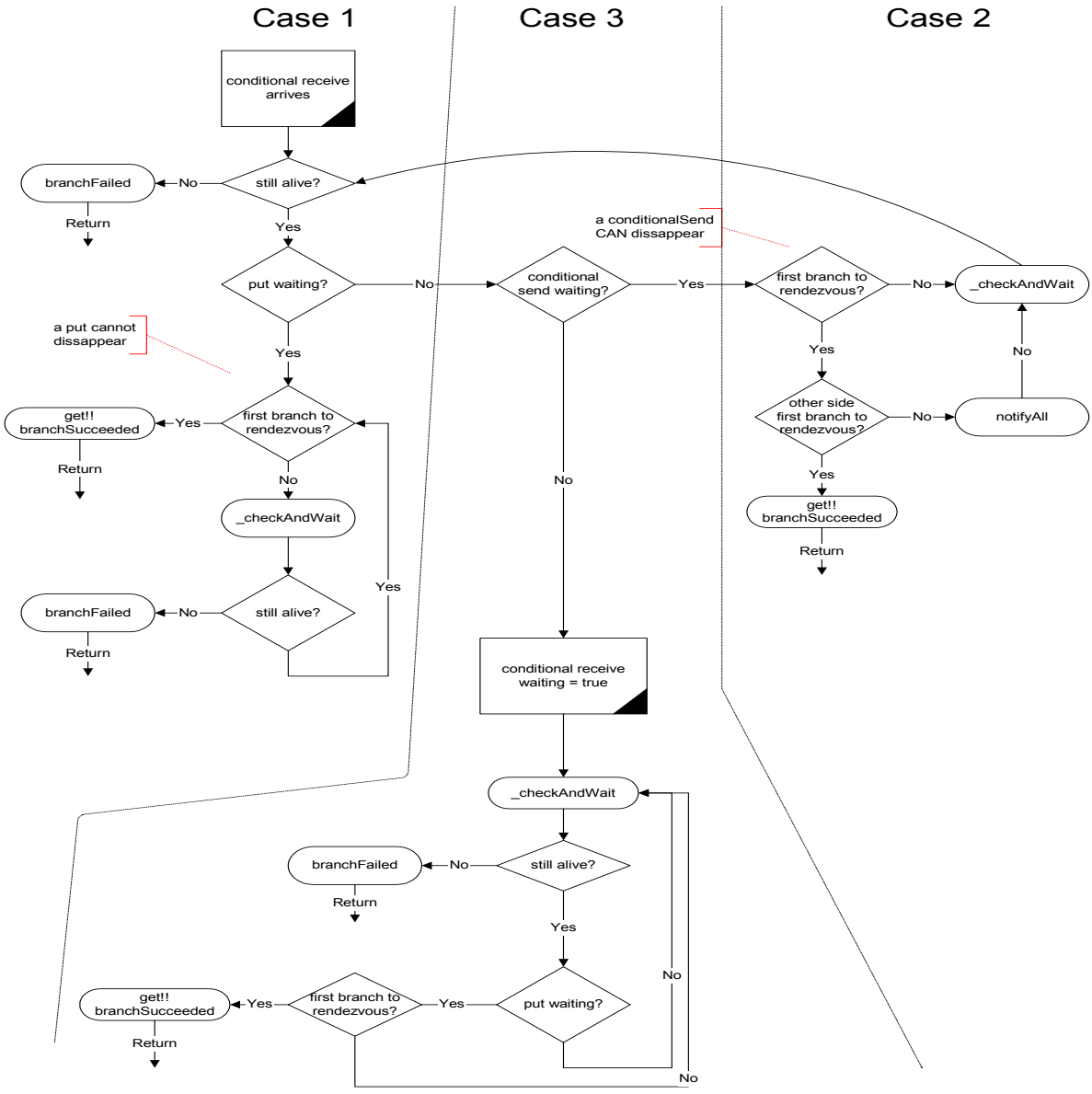

FIGURE 6.12. Algorithm used to determine if a conditional rendezvous branch succeeds or fails

the algorithm is shown in the dashed ellipse in figure 6.13. It does not affect the algorithm except in the case when a conditional send is waiting when a get arrives at the receiver. In this case the process that calls the get should wait on the receiver until the conditional send waiting flag is false. If the conditional send succeeded, and hence executed a put, then the get waiting flag and the conditional send waiting flag should both be false and the actor proceeds through to the third step of the rendezvous. If the conditional send failed, it will have reset the conditional send waiting flag and issued a notifyAll() on the receiver, thus waking up the get and allowing it to properly wait for a put.

The same reasoning also applies to the case when a conditional receive arrives at a receiver before a put.

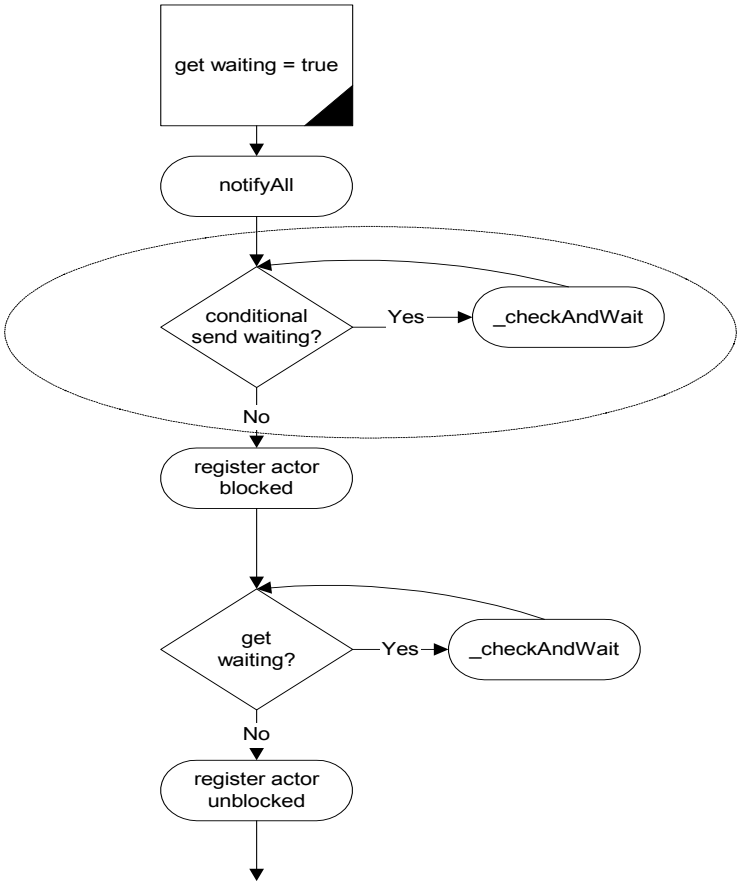

FIGURE 6.13. Modification of rendezvous algorithm, section 6.6.3, shown in ellipse.

7

DDE Domain

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7.1 Introduction

The distributed discrete-event (DDE) model of computation incorporates a distributed notion of time into a dataflow style of computation. Time progresses in a DDE model when the actors in the model execute and communicate. Actors in a DDE model communicate by sending messages through bounded, FIFO channels. Time in a DDE model is distributed and localized, and the actors of a DDE model each maintain their own local notion of the current time. Local time information is shared between two connected actors whenever a communication between said actors occurs. Conversely, communication between two connected actors can occur only when constraints on the relative local time information of the actors are adhered to.

The DDE domain is based on distributed discrete-event processing and leverages a wealth of research devoted to this topic. Some tutorial publications on this topic are [23][33][53][92]. The DDE domain implements a specific variant of distributed discrete event systems (DDES) as expounded by Chandy and Misra [23]. The domain serves as a framework for studying DDES with two special emphases. First we consider DDES from a dataflow perspective; we view DDE as an implementation of the Kahn dataflow model [55] with distributed time added on top. Second we study DDES not with the goal of improving execution speed (as has been the case traditionally). Instead we study DDES to learn its usefulness in modeling and designing systems that are timed and distributed.

7.2 Using DDE

The DDE domain is typed so that actors used in a model must be derived from TypedAtomicActor. The DDE domain is designed to use both DDE specific actors as well as domain-polymorphic actors. DDE specific actors take advantage of DDEActor and DDEIOPort which are designed to provide convenient support for specifying time when producing and consuming tokens. The DDE domain also has special restrictions on how feedback is specified in models.

7.2.1 DDEActor

The DDE model of computation makes one very strong assumption about the execution of an actor: *all input ports of an actor operating in a DDE model must be regularly polled to determine which input channel has the oldest pending event*. Any actor that adheres to this assumption can operate in a DDE model. Thus, many polymorphic actors found in ptolemy/actor/[lib, gui] are suitable for operation in DDE models. For convenience, DDEActor was developed to simplify the construction of actors that have DDE semantics. DDEActor has two key methods as follows:

getNextToken(). This method polls each input port of an actor and returns the (non-Null) token that represents the oldest event. This method blocks accordingly as outlined in section 7.3.1 (Communicating Time).

getLastPort(). This method returns the input IOPort from which the last (non-Null) token was consumed. This method presumes that getNextToken() is being used for token consumption.

7.2.2 DDEIOPort

DDEIOPort extends TypedIOPort with parameters for specifying time stamp values of tokens that are being sent to neighboring actors. Since DDEIOPort extends TypedIOPort, use of DDEIOPorts will not violate the type resolution protocol. DDEIOPort is not necessary to facilitate communication between actors executing in a DDE model; standard TypedIOPorts are sufficient in most communication. DDEIOPorts become useful when the time stamp to be associated with an outgoing token is greater than the current time of the sending actor. Hence, DDEIOPorts are only useful in conjunction with delay actors (see “Enabling Communication: Advancing Time” on page 7-103, for a definition of delay actor). Most polymorphic actors available for Ptolemy II are not delay actors.

7.2.3 Feedback Topologies

In order to execute models with feedback cycles that will not deadlock, FeedBackDelay actors must be used. FeedBackDelay is found in the DDE kernel package. FeedBackDelay actors do not perform computation, but instead increment the time stamps of tokens that flow through them by a specified delay. The delay value of a FeedBackDelay actor must be chosen to be less than the delta time of the feedback cycle in which the FeedBackDelay actor is contained. Elaborate delay values can be specified by overriding the getDelay() method in subclasses of FeedBackDelay. An example can be found in ptolemy/domains/dde/demo/LocalZeno/ZenoDelay.java.

A difficulty found in feedback cycles occurs during the initialization of a model’s execution. In figure 7.1 we see that even if Actor B is a FeedBackDelay actor, the system will deadlock if the first event is created by *A* since *C* will block on an event from *B*. To alleviate this problem a special time stamp value has been reserved: PrioritizedTimedQueue.IGNORE. When an actor encounters an event with a time stamp of IGNORE (an *ignore event*), the actor will ignore the event and the input channel

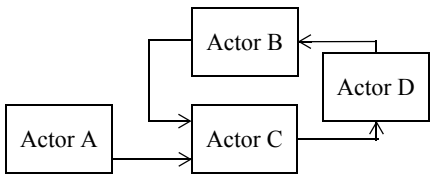

FIGURE 7.1. Initializing feedback topologies.

it is associated with. The actor then considers the other input channels in determining the next available event. After a non-ignore event is encountered and consumed by the actor, all ignore events will be cleared from the receivers. If all of an actor's input channels contain ignore events, then the actor will clear all ignore events and then proceed with normal operation.

The initialize method of FeedBackDelay produces an ignore event. Thus, in figure 7.1, if *B* is a FeedBackDelay actor, the ignore event it produces will be sent to *C*'s upper input channel allowing *C* to consume the first event from *A*. The production of null tokens and feedback delays will then be sufficient to continue execution from that point on. Note that the production of an ignore event by a FeedBackDelay actor serves as a major distinction between it and all other actors. *If a delay is desired simply to represent the computational delay of a given model, a FeedBackDelay actor should not be used*.

The intricate operation of ignore events requires special consideration when determining the position of a FeedBackDelay actor in a feedback cycle. A FeedBackDelay actor should be placed so that the ignore event it produces will be ignored in deference to the first real event that enters a feedback cycle. Thus, choosing actor *D* as a FeedBackDelay actor in figure 7.1 would not be useful given that the first real event entering the cycle is created by *A*.

7.3 Properties of the DDE domain

Operationally, the semantics of the DDE domain can be separated into two functionalities. The first functionality relates to how time advances during the communication of data and how communication proceeds via blocking reads and writes. The second functionality considers how a DDE model prevents deadlock due to local time dependencies. The technique for preventing deadlock involves the communication of *null messages* that consist solely of local time information.

7.3.1 Enabling Communication: Advancing Time

Communicating Tokens. A DDE model consists of a network of sequential actors that are connected via unidirectional, bounded, FIFO queues. Tokens are sent from a sending actor to a receiving actor by placing a token in the appropriate queue where the token is stored until the receiving actor consumes it. As in the process networks domain, the execution of each actor is controlled by a process. If a process attempts to read a token from a queue that is empty, then the process will block until a token becomes available on the channel. If a process attempts to write a token to a queue that is full, then the process will block until space becomes available for more tokens in that queue. Note that this blocking read/write paradigm is equivalent to the operational semantics found in non-timed process networks (PN) as implemented in Ptolemy II (see the PN Domain chapter).

If all processes in a DDE model simultaneously block, then the model deadlocks. If a deadlock is due to processes that are either waiting to read from an empty queue, *read blocks*, or waiting to write to a full queue, *write blocks*, then we say that the model has experienced *non-timed deadlock*. Non-timed deadlock is equivalent to the notion of deadlock found in bounded process networks scheduling problems as outlined by Parks [103]. If a non-timed deadlock is due to a model that consists solely of processes that are read blocked, then we say that a *real deadlock* has occurred and the model is terminated. If a non-timed deadlock is due to a model that consists of at least one process that is write blocked, then the capacity of the full queues are increased until deadlock no longer exists. Such deadlocks are called *artificial deadlock*, and the policy of increasing the capacity of full queues as shown by Parks can guarantee the execution of a model in bounded memory whenever possible.

Communicating Time. Each actor in a DDE model maintains a local notion of time. Any non-negative real number may serve as a valid value of time. As tokens are communicated between actors, time stamps are associated with each token. Whenever an actor consumes a token, the actor's *current time* is set to be equal to that of the consumed token's time stamp. The time stamp value applied to outgoing tokens of an actor is equivalent to that actor's *output time*. For actors that model a process in which there is delay between incoming time stamps and corresponding outgoing time stamps, then the output time is always greater than the current time; otherwise, the output time is equal to the current time. We refer to actors of the former case as *delay actors*.

For a given queue containing time stamped tokens, the time stamp of the first token currently contained by the queue is referred to as the *receiver time* of the queue. If a queue is empty, its receiver time is the value of the time stamp associated with the last token to flow through the queue, or 0.0 if no tokens have traveled through the queue. An actor may consume a token from an input queue given that the queue has a token available and the receiver time of the queue is less than the receiver times of all other input queues of the actor. If the queue with the smallest receiver time is empty, then the actor blocks until this queue receives a token, at which time the actor considers the updated receiver time in selecting a queue to read from. The *last time* of a queue is the time stamp of the last token to be placed in the queue. If no tokens have been placed in the queue, then the last time is 0.0

Figure 7.2 shows three actors, each with three input queues. Actor *A* has two tokens available on the top queue, no tokens available on the middle queue and one token available on the bottom queue. The receiver times of the top, middle and bottom queue are respectively, 17.0, 12.0 and 15.0. Since the queue with the minimum receiver time (the middle queue) is empty, *A* blocks on this queue before it proceeds. In the case of actor *B*, the minimum receiver time belongs to the bottom queue. Thus, *B* proceeds by consuming the token found on the bottom queue. After consuming this token, *B* compares all of its receiver times to determine which token it can consume next. Actor *C* is an example of an actor that contains multiple input queues with identical receiver times. To accommodate this situation, each actor assigns a unique priority to each input queue. An actor can consume a token from a queue if no other queue has a lower receiver time and if all queues that have an identical receiver time also have a lower priority.

Each receiver has a *completion time* that is set during the initialization of a model. The completion time of the receiver specifies the time after which the receiver will no longer operate. If the time stamp of the oldest token in a receiver exceeds the completion time, then that receiver will become *inactive*.

7.3.2 Maintaining Communication: Null Tokens

Deadlocks can occur in a DDE model in a form that differs from the deadlocks described in the previous section. This alternative form of deadlock occurs when an actor read blocks on an input port even though it contains other ports with tokens. The topology of a DDE model can lead to deadlock as read blocked actors wait on each other for time stamped tokens that will never appear. Figure 7.3 illus-

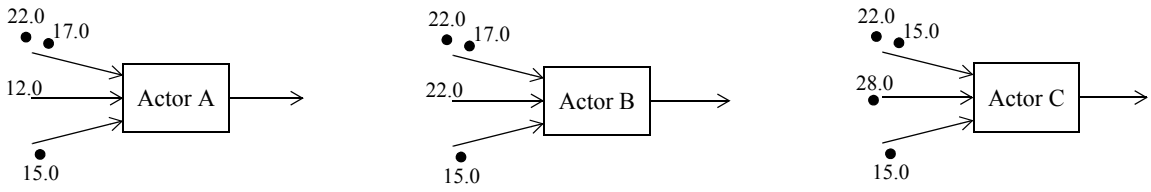

FIGURE 7.2. DDE actors and local time.

trates this problem. In this topology, consider a situation in which actor *A* only creates tokens on its lower output queue. This will lead to tokens being created on actor *C*'s output queue but no tokens will be created on *B*'s output queue (since *B* has no tokens to consume). This situation results in *D* read blocking indefinitely on its upper input queue even though it is clear that no tokens will ever flow through this queue. The result: *timed deadlock!* The situation shown in figure 7.3 is only one example of timed deadlock. In fact there are two types of timed deadlock: *feedforward* and *feedback*.

Figure 7.3 is an example of feedforward deadlock. Feedforward deadlock occurs when a set of connected actors are deadlocked such that all actors in the set are read blocked and at least one of the actors in the set is read blocked on an input queue that has a receiver time that is less than the local clock of the input queue's source actor. In the example shown above, the upper input queue of *B* has a receiver time of 0.0 even though the local clock of *A* has advanced to 8.0.

Feedback deadlock occurs when a set of cyclically connected actors are deadlocked such that all actors in the set are read blocked and at least one actor in the set, say actor *X*, is read blocked on an input queue that can read tokens which are directly or indirectly a result of output from that same actor (actor *X*). Figure 7.4 is an example of feedback timed deadlock. Note that *B* can not produce an output based on the consumption of the token timestamped at 5.0 because it must wait for a token on the upper input that depends on the output of *B*!

Preventing Feedforward Timed Deadlock. To address feedforward timed deadlock, *null tokens* are employed. A null token provides an actor with a means of communicating time advancement even though data (*real* tokens) are not being transmitted. Whenever an actor consumes a token, it places a null token on each of its output queues such that the time stamp of the null token is equal to the current time of the actor. Thus, if actor *A* of figure 7.3, produced a token on its lower output queue at time 5.0, it would also produce a null token on its upper output queue at time 5.0.

If an actor encounters a null token on one of its input queues, then the actor does the following. First it consumes the tokens of all other input queues it contains given that the other input queues have receiver times that are less than or equal to the time stamp of the null token. Next the actor removes the null token from the input queue and sets its current time to equal the time stamp of the null token. The actor then places null tokens time stamped to the current time on all output queues that have a last time that is less then the actor's current time. As an example, if *B* in figure 7.3 consumes a null token on its input with a time stamp of 5.0 then it would also produce a null token on its output with a time stamp

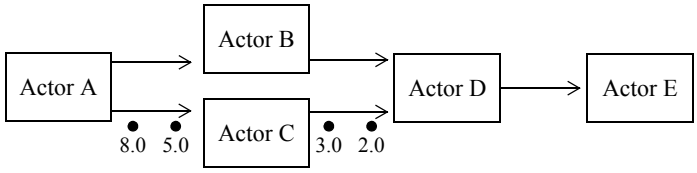

FIGURE 7.3. Timed deadlock (feedforward).

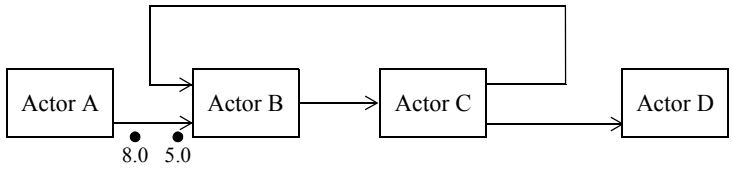

FIGURE 7.4. Timed deadlock (feedback).

of 5.0.

The result of using null tokens is that time information is evenly propagated through a model's topology. The beauty of null tokens is that they inform actors of inactivity in other components of a model without requiring centralized dissemination of this information. Given the use of null tokens, feedforward timed deadlock is prevented in the execution of DDE models. It is important to recognize that null tokens are used solely for the purpose of avoiding deadlocks. Null tokens do not represent any actual components of the physical system being modeled. Furthermore, the production of a null token that is the direct result of the consumption of a null token is not considered computation from the standpoint of the system being modeled. The idea of null tokens was first espoused by Chandy and Misra [23].

Preventing Feedback Timed Deadlock. We address feedback timed deadlock as follows. All feedback loops are required to have a cumulative time stamp increment that is greater than zero. In other words, feedback loops are required to contain delay actors. Peacock, Wong and Manning [104] have shown that a necessary condition for feedback timed deadlock is that a feedback loop must contain no delay actors. The delay value (delay = output time - current time) of a delay actor must be chosen wisely; it must be less then the smallest delta time of all other actors contained in the same feedback loop. *Delta time* is the difference between the time stamps of a token that is consumed by an actor and the corresponding token that is produced in direct response. If a system being modeled has characteristics that prevent a fixed, positive lower bound on delta time from being specified, then our approach can not solve feedback timed deadlock. Such a situation is referred to as a *Zeno condition*. An application involving an approximated Zeno condition is discussed in section 7.5 below.

The DDE software architecture provides one delay actor for use in preventing feedback timed deadlock: *FeedBackDelay*. See "Feedback Topologies" on page 7-102 for further details about this actor.

7.3.3 Alternative Distributed Discrete Event Methods

The field of distributed discrete event simulation, also referred to as parallel discrete event simulation (PDES), has been an active area of research since the late 1970's [23][33][53][92][104]. Recently there has been a resurgence of activity [8][9][14]. This is due in part to the wide availability of distributed frameworks for hosting simulations and the application of parallel simulation techniques to non-research oriented domains. For example, several WWW search engines are based on network of workstation technology.

The field of distributed discrete event simulation can be cast into two camps that are distinguished by the blocking read approach taken by the actors. One camp was introduced by Chandy and Misra [23][33][92][104] and is known as *conservative* blocking. The second camp was introduced by David Jefferson through the Jet Propulsion Laboratory Time Warp system and is referred to as the *optimistic* approach [53][33]. In certain problems, the optimistic approach executes faster than the conservative approach, nevertheless, the gains in speed result in significant increases in program memory. The conservative approach does not perform faster than the optimistic approach but it executes efficiently for all classes of discrete event systems. Given the modeling semantics emphasis of Ptolemy II, performance (speed) is not considered a premium. Furthermore, Ptolemy II's embedded systems emphasis suggests that memory constraints are likely to be strict. For these reasons, the implementation found in the DDE domain follows the conservative approach.

7.4 The DDE Software Architecture

For a model to have DDE semantics, it must have a DDEDirector controlling it. This ensures that the receivers in the ports are DDEReceivers. Each actor in a DDE model is under the control of a DDEThread. DDEThreads contain a TimeKeeper that manages the local notion of time that is associated with the DDEThread's actor.

7.4.1 Local Time Management

The UML diagram of the local time management system of the DDE domain is shown in figure 7.5 and consists of PrioritizedTimedQueue, DDEReceiver, DDEThread and TimeKeeper. Since time is localized, the DDEDirector does not have a direct role in this process. Note that DDEReceiver is derived from PrioritizedTimedQueue. The primary purpose of PrioritizedTimedQueue is to keep track of a receiver's local time information. DDEReceiver adds blocking read/write functionality to PrioritizedTimedQueue.

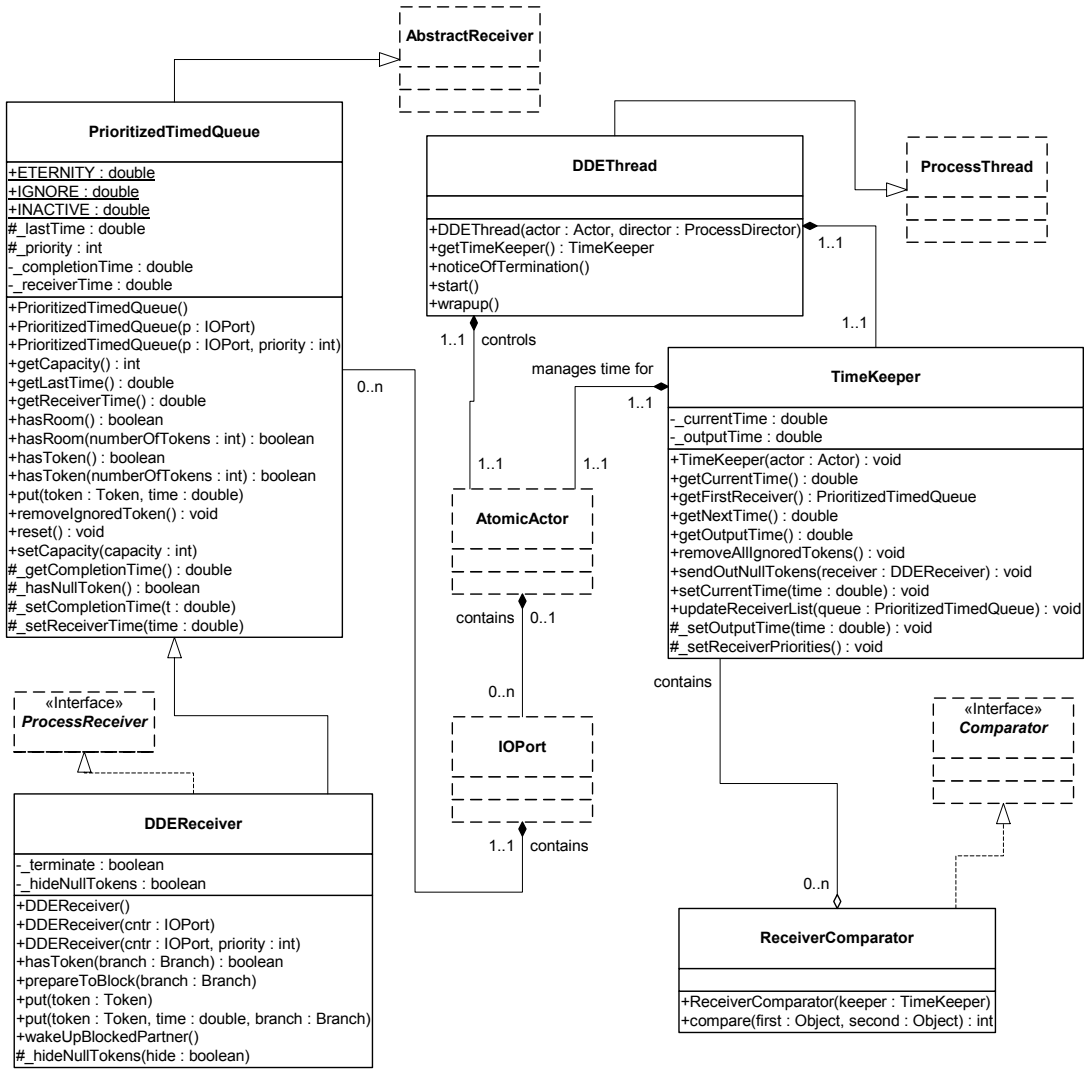

FIGURE 7.5. Key classes for managing time locally.

When a DDEDirector is initialized, it instantiates a DDEThread for each actor that the director manages. DDEThread is derived from ProcessThread. The ProcessThread class provides functionality that is common to all of the process domains (e.g., CSP, DDE and PN). The directors of all process domains (including DDE) assign a single actor to each ProcessThread. ProcessThreads take responsibility of their assigned actor's execution by invoking the iteration methods of the actor. The iteration methods are prefire(), fire() and postfire(); ProcessThreads also invoke wrapup() on the actors they control.

DDEThread extends the functionality of ProcessThread. Upon instantiation, a DDEThread creates a TimeKeeper object and assigns this object to the actor that it controls. The TimeKeeper gets access to each of the DDEReceivers that the actor contains. Each of the receivers can access the TimeKeeper and through the TimeKeeper the receivers can then determine their relative receiver times. With this information, the receivers are fully equipped to apply the appropriate blocking rules as they get and put time stamped tokens.

DDEReceivers use a dynamic approach to accessing the DDEThread and TimeKeeper. To ensure domain polymorphism, actors (DDE or otherwise) do not have static references to the TimeKeeper and DDEThread that they are controlled by. To ensure simplified mutability support, DDEReceivers do not have a static reference to TimeKeepers. Access to the local time management facilities is accomplished via the Java Thread.currentThread() method. Using this method, a DDEReceiver dynamically accesses the thread responsible for invoking it. Presumably the calling thread is a DDEThread and appropriate steps are taken if it is not. Once the DDEThread is accessed, the corresponding TimeKeeper can be accessed as well. The DDE domain uses this approach extensively in DDEReceiver.put(Token) and DDEReceiver.get().

7.4.2 Detecting Deadlock

The other kernel classes of the DDE domain are shown in figure 7.6. The purpose of the DDEDirector is to detect and (if possible) resolve timed and/or non-timed deadlock of the model it controls. Whenever a receiver blocks, it informs the director. The director keeps track of the number of active processes, and the number of processes that are either blocked on a read or write. Artificial deadlocks are resolved by increasing the queue capacity of write-blocked receivers.

Note the distinction between internal and external read blocks in DDEDirector's package friendly methods. The current release of DDE assumes that actors that execute according to a DDE model of computation are atomic rather than composite. In a future Ptolemy II release, composite actors will be facilitated in the DDE domain. At that time, it will be important to distinguish internal and external read blocks. Until then, only internal read blocks are in use.

7.4.3 Ending Execution

Execution of a model ends if either an unresolvable deadlock occurs, the director's completion time is exceeded by all of the actors it manages, or early termination is requested (e.g., by a user interface button). The director's completion time is set via the public *stopTime* parameter of DDEDirector. The completion time is passed on to each DDEReceiver. If a receiver's receiver time exceeds the completion time, then the receiver becomes inactive. If all receivers of an actor become inactive and the actor is not a source actor, then the actor will end execution and its wrapup() method will be called. In such a scenario, the actor is said to have terminated *normally.*

Early terminations and unresolvable deadlocks share a common mechanism for ending execution. Each DDEReceiver has a boolean `_terminate` flag. If the flag is set to true, then the receiver will

throw a `TerminateProcessException` the next time any of its methods are invoked. TerminateProcessExceptions are part of the `ptolemy/actor/process` package and ProcessThreads know to end an actor's execution if this exception is caught. In the case of unresolvable deadlock, the `_terminate` flag of all blocked receivers is set to true. The receivers are then awakened from blocking and they each throw the exception.

7.5 Example DDE Applications

To illustrate distributed discrete event execution, we have developed an applet that features a feedback topology and incorporates polymorphic as well as DDE specific actors. The model, shown in figure 7.7, consists of a single source actor (ptolemy/actor/lib/Clock) and an upper and lower branch of four actors each. The upper and lower branches have identical topologies and are fed an identical stream of tokens from the Clock source with the exception that in the lower branch ZenoDelay replaces FeedBackDelay.

As with all feedback topologies in DDE (and DE) models, a positive time delay is necessary in feedback loops to prevent deadlock. If the time delay of a given loop is lower bounded by zero but can not be guaranteed to be greater than a fixed positive value, then a Zeno condition can occur in which time will not advance beyond a certain point even though the actors of the feedback loop continue to execute without deadlocking. ZenoDelay extends FeedBackDelay and is designed so that a Zeno condition will be encountered. When execution of the model begins, both FeedBackDelay and ZenoDelay

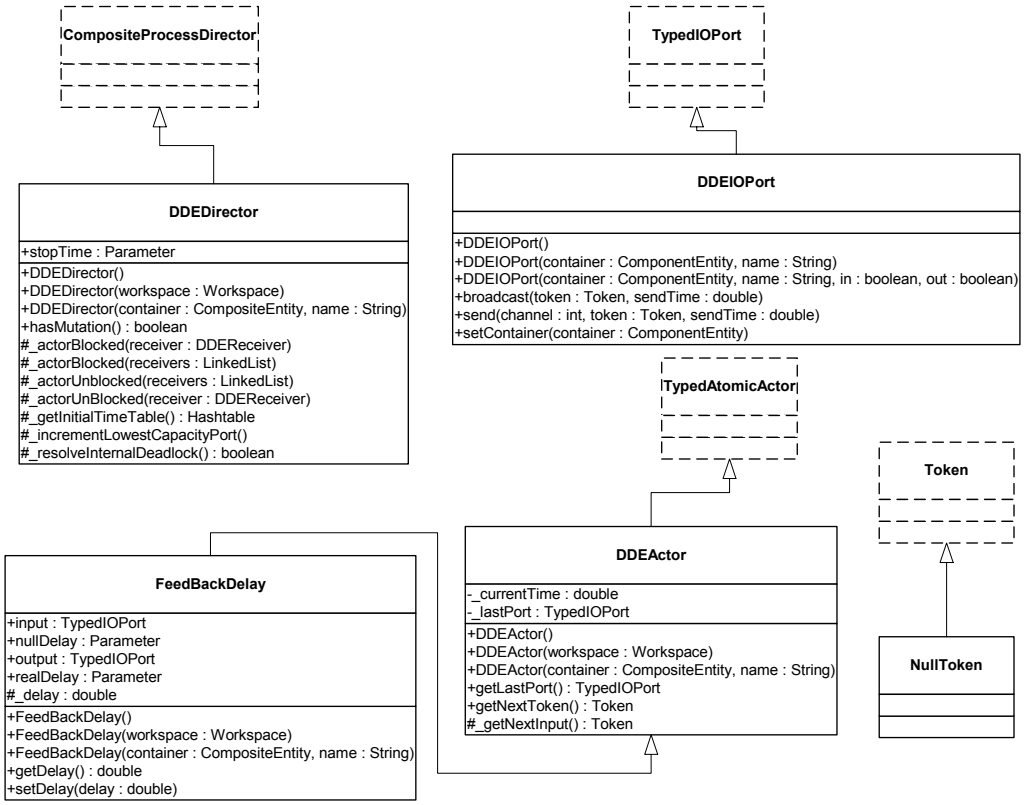

FIGURE 7.6. Additional classes in the DDE kernel.

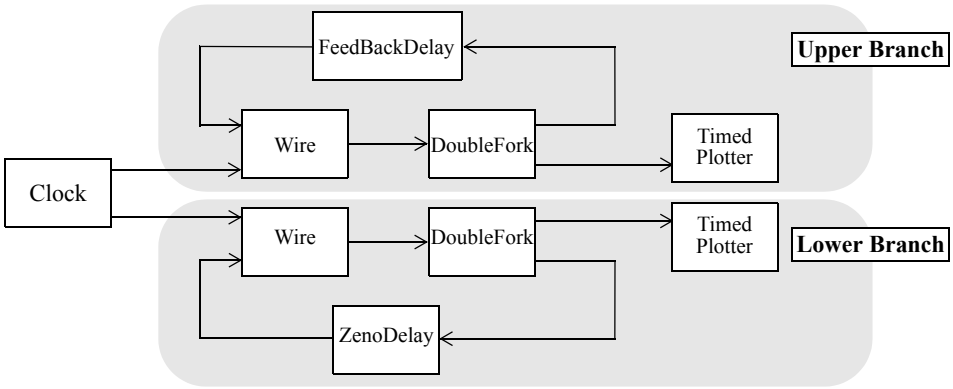

FIGURE 7.7. Localized Zeno condition topology.

are used to feed back null tokens into Wire so that the model does not deadlock. After local time exceeds a preset value, ZenoDelay reduces its delay so that the lower branch approximates a Zeno condition.

In centralized discrete event systems, Zeno conditions prevent progress in the entire model. This is true because the feedback cycle experiencing the Zeno condition prevents time from advancing in the entire model. In contrast, distributed discrete event systems localize Zeno conditions as much as is possible based on the topology of the system. Thus, a Zeno condition can exist in the lower branch and the upper branch will continue its execution unimpeded. Localizing Zeno conditions can be useful in large scale modeling in which a Zeno condition may not be discovered until a great deal of time has been invested in execution of the model. In such situations, partial data collection may proceed prior to correction of the delay error that resulted in the Zeno condition.

8

PN Domain

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8.1 Introduction

The process networks (PN) domain in Ptolemy II models a system as a network of processes that communicate with each other by passing messages through unidirectional first-in-first-out (FIFO) channels. A process blocks when trying to read from an empty channel until a message becomes available on it. This model of computation is deterministic in the sense that the sequence of values communicated on the channels is completely determined by the model. Consequently, a process network can be evaluated using a complete parallel or sequential schedule and every schedule in between, always yielding the same output results for a given input sequence.

PN is a natural model for describing signal processing systems where infinite streams of data samples are incrementally transformed by a collection of processes executing in parallel. Embedded signal processing systems are good examples of such systems. They are typically designed to operate indefinitely with limited resources. This behavior is naturally described as a process network that runs forever but with bounded buffering on the communication channels whenever possible.[1]

PN can also be used to model concurrency in the various hardware components of an embedded system. The original process networks model of computation can model the functional behavior of these systems and test them for their functional correctness, but it cannot directly model their real-time behavior. To address the involvement of time, we have extended the PN model such that it can include the notion of time.

Some systems might display adaptive behavior like migrating code, agents, and arrivals and departures of processes. To support this adaptive behavior, we provide a mutation mechanism that supports addition, deletion, and changing of processes and channels. With untimed PN, this might display non-

1. In general, bounded buffers cannot be ensured for an arbitrary process network. An important part of the design of a process network concerns showing that the buffers are, in fact, bounded. Synchronous dataflow models are an important type of process network which always have bounded buffers.

determinism, while with timed-PN, it becomes deterministic.

The PN model of computation is a superset of the synchronous dataflow model of computation (see the SDF Domain chapter). Consequently, any SDF actor can be used within the PN domain. Similarly any domain-polymorphic actor can be used in the PN domain. However, the execution of the model is very different from SDF, since a separate process is created for each actor. These processes are implemented as Java threads [99].

8.2 Using PN

There are two issues to be dealt with in the PN domain:

- Deadlock in feedback loops
- Designing actors

8.2.1 Deadlock in Feedback Loops

Feedback loops must be handled in much the same way as in the SDF domain. One of the actors in the feedback loop must create a number of tokens in its feedback loop in order to break the data dependency. Just like in the SDF domain, the SampleDelay actor can be used for this purpose. Remember, however that the PN domain does not (and cannot) statically analyze the model to determine the size of the delay necessary in the feedback loop. It is up to the designer of the model to specify the correct amount of delay.

8.2.2 Designing Actors

Because of the way the PN domain is implemented, it is not possible for an actor to check if data is present on an input port. The hasToken() method always returns true indicating that a token is present, and if a token is not actually present, then the get() method will block until one becomes available. This allows models to execute deterministically. However, actors that take inputs from more than one input can often be difficult to write. The common way of creating such an actor is similar to the way the Select actor works. A control input is read first, and the data from that port determines which input port to read from.

8.3 Properties of the PN domain

Two important properties of the PN domain implemented in Ptolemy II are that processes communicate asynchronously (by ordered queues) and that the memory used in the communication is bounded whenever possible. The PN domain in Ptolemy II can be used with or without a notion of time.

8.3.1 Asynchronous Communication

Kahn and MacQueen [54][55] describe a model of computation where processes are connected by communication channels to form a network. Processes produce data elements or *tokens* and send them along a unidirectional communication channel where they are stored in a FIFO queue until the destination process consumes them. This is a form of asynchronous communication between processes. Communication channels are the *only* method processes may use to exchange information. A set of processes that communicate through a network of FIFO queues defines a *program*.

Kahn and MacQueen require that execution of a process be suspended when it attempts to get data from an empty input channel (*blocking reads*). Hence, a process may not poll a channel for presence or absence of data. At any given point, a process is either doing some computation (enabled) or it is blocked waiting for data (*read blocked*) on exactly one of its input channels; it cannot wait for data from more than one channel simultaneously. Systems that obey this model are determinate; the history of tokens produced on the communication channels does not depend on the execution order. Therefore, the results produced by executing a program are not affected by the scheduling of the various processes.

In case all the processes in a model are blocked while trying to read from some channel, then we have a *real deadlock*; none of the processes can proceed. Real deadlock is a program state that happens irrespective of the schedule chosen for the processes in a model. This characteristic is guaranteed by the determinacy property of process networks.

8.3.2 Bounded Memory Execution

The high level of concurrency in process networks makes it an ideal match for embedded system software and for modeling hardware implementations. A characteristic of these embedded applications and hardware processes, is that they are intended to run indefinitely with a limited amount of memory. One problem with directly implementing the Kahn-MacQueen semantics is that bounded memory execution of a process network is not guaranteed, even if it is possible. Hence, bounded memory execution of process networks becomes crucial for its usefulness for hardware and embedded software.

Parks [103] addresses this aspect of process networks and provides an algorithm to make a process network application execute in bounded memory whenever possible. He provides an implementation of the Kahn-MacQueen semantics using *blocking writes* that assigns a fixed capacity to each FIFO channel and forces processes to block temporarily if a channel is full. Thus a process has now three states: *running* (*executing*), *read blocked*, or *write blocked* and a process may not poll a channel for either data or room.

In addition to the real deadlock described above, the introduction of a blocking write operation can cause an *artificial deadlock* of the process network. In this situation, all the processes in a model are blocked and at least one process is blocked on a write. However unlike after real deadlock, a program can continue after artificial deadlock by increasing the capacity of the channels on which processes are write blocked. In particular, Parks chooses to increase only the capacity of the channel with the smallest capacity among the channels on which processes are write blocked. This algorithm minimizes overall required memory in the channels and is used in the PN domain to handled artificial deadlock.

8.3.3 Time

In real-time systems and embedded applications, the real time behavior of a system is as important as the functional correctness. Process networks can be used to describe the functional properties of a system, but cannot describe temporal properties since the basic model lacks the notion of time. One solution is to use some other timed model of computation, such as DE, for describing temporal properties. Another solution is to extend the process networks model of computation with a notion of time, as we have done in Ptolemy II. This extension is based on the Pamela model [36], which was originally developed for modeling the performance of parallel systems using Dykstra's semaphores.

In the timed PN domain, time is global. All processes in a model share the same time, which is referred to as the *current time* or *model time*. A process can explicitly wait for time to advance, by *delaying* itself for some fixed amount of time. After being suspended for the specified amount of time,

the process wakes up and continues to execute. If the process delays itself for zero time then the process simply continues to execute.

In the timed PN domain, time changes only at specific moments and never during the execution of a process. The time observed by a process can only advance when it is in one of the following two states:

1. The process is delayed and is explicitly waiting for time to advance (*delay block*).
2. The process is waiting for data to arrive on one of its input channels (*read block*).

When all the processes in a program are in one of these two states, then the program is in a state of *timed deadlock*. The fact that at least one process is delayed, distinguishes timed deadlock from other deadlocks. When timed deadlock is detected, the current time is advanced until at least one process can wake up from a delay block and the model continues executing.

8.3.4 Mutations

The PN domain tolerates mutations, which are run-time changes in the model structure. Normally, mutations are realized as *change requests* queued with the model. In PN there is no determinate point where mutations can occur other than a real deadlock. However, being able to perform mutations at this point is unlikely as a real deadlock might never occur. For example, a model with even one non-terminating source never experiences a real deadlock. Therefore mutations cannot be performed at determinate points since the processes in the network are not synchronized. Executing mutations at arbitrary times introduces non-determinism in PN, since the state of the processes is unknown.

In timed PN, however, the presence of timed deadlock provides a regular point at which the state of execution can be determined. This means that mutations in timed PN can be made deterministically. Implementation details are presented later in section 8.4.

8.4 The PN Software Architecture

The PN domain kernel is realized in package ptolemy.domains.pn.kernel. The structure diagram of the package is shown in figure 8.1.

8.4.1 PNDirector

This class extends the CompositeProcessDirector base class to add Kahn process networks (PN) semantics. This director does not support mutations or a notion of time. It provides only a mechanism to perform blocking reads and writes using bounded memory execution whenever possible.

This director is capable of handling both real and artificial deadlocks. Artificial deadlock is resolved as soon as it arises using Parks' algorithm as explained in section 8.3.2. Real deadlock, however, cannot be handled locally and must rely on the external environment to provide more data for execution to continue.

PNDirector has a parameter called *initialQueueCapacity* that sets the initial capacities of the queues in all the receivers created in the PN domain. Another parameter, *maximumQueueCapacity*, sets the upper bound on the queue capacities.

8.4.2 TimedPNDirector

TimedPNDirector extends the PNDirector to introduces a notion of global time to the model. It

also provides for deterministic execution of mutations. Mutations are performed at the earliest timed-deadlock that occurs after they are queued. Since occurrence of timed-deadlock is deterministic, performing mutations at this point makes mutations deterministic.

8.4.3 PNQueueReceiver

The PNQueueReceiver implements the ProcessReceiver interface and contains a FIFO queue to represent a process network communications channel. These receivers are also responsible for implementing the blocking reads and blocking writes through the get() and put() methods.

When the get() method is called, the receiver first checks whether its FIFO queue has any token. If not, then it reports to the director that the reading thread is blocked waiting for data. It also sets an internal flag to indicate that a thread is read blocked. Then the reading thread is suspended until some other thread puts a token into the FIFO queue. At this point, the flag of the receiver is reset to false, the director is notified that a process has unblocked, the reading process retrieves the first token from the FIFO queue and execution continues.

The put() method of the receiver works similarly by first checking whether the FIFO queue is full to capacity. If so, it reports to the director that the writing thread is blocked waiting for space in the queue. It also sets an internal flag to indicate that a thread is write blocked. The writing thread blocks until some other thread gets a token from the FIFO queue, or the size of the queue is increased by the director because the model reached an artificial deadlock. In either case, the director is notified that a writing process unblocks and the internal flag is reset. The writing thread is waked up and its token is placed into the receiver.

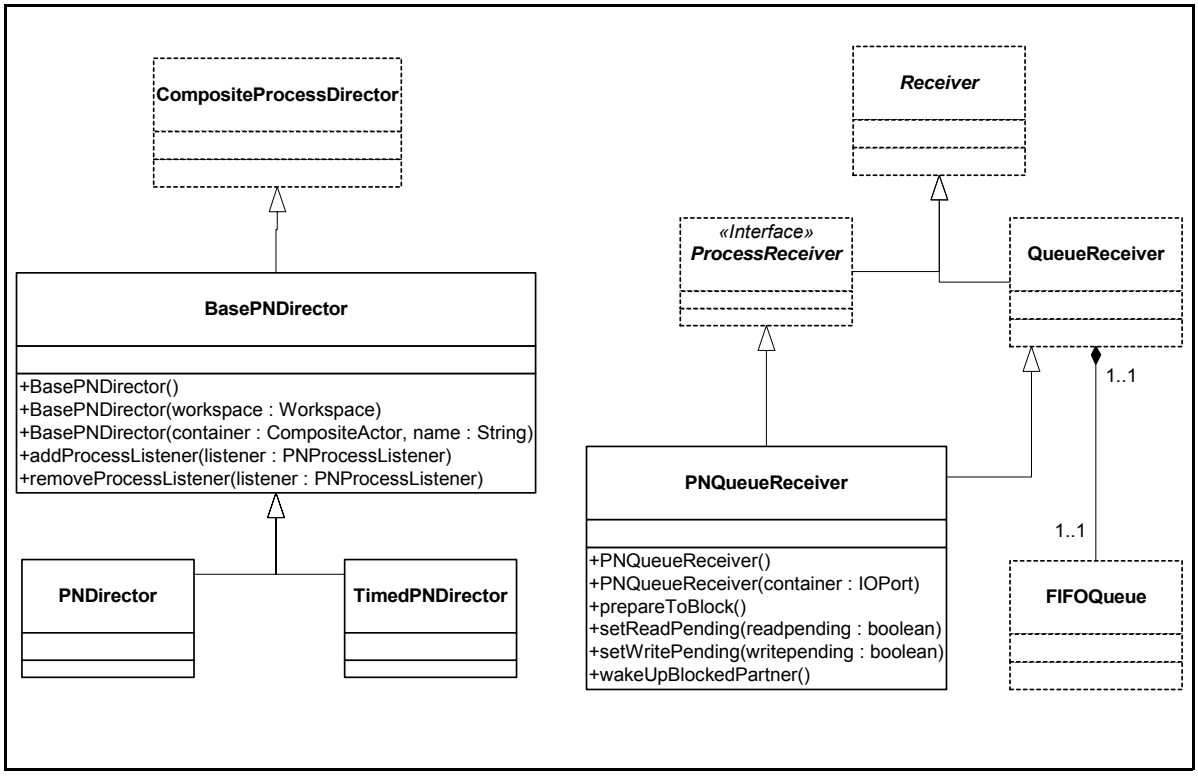

FIGURE 8.1. Static structure of the PN kernel.

8.4.4 Handling Deadlock

Every time an actor in PN blocks, the count of blocked actors is incremented. If the total number of actors blocked or paused by user request equals the total number of actors active in the simulation, a deadlock is detected. On detection of a deadlock, if one or more actors are blocked on a write, then this is an artificial deadlock. The channel with the smallest capacity among all the channels with actors blocked on a write is chosen and its capacity is doubled. This implements the bounded memory execution as suggested by [103]. If a real deadlock is detected, then the fire() method of the director returns, allowing a containing model to present more data to the inputs of the process network.

8.4.5 Finite Iterations

An important aspect of Ptolemy II is that the firing of an actor, or an entire model is guaranteed to complete. In the process domains the end of a firing occurs when deadlock is reached. The deadlock can be real or timed deadlock. However, in a process network real deadlock may never actually happen. In this case, in order to manually stop execution or to execute mutations there needs to be a way to halt all the executing threads in the network. This is handled by the stopFire() method of the executable interface. The process director implements this method to set a flag in each process which causes the process to pause. Note that as with most domains, it is not possible to simply call the wrapup() method of the process director, since the fire method has not yet returned.

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Index