MOONLIGHT

VOID Shell Specification

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Abstract

This document gives the specification of the `VOID Shell` described in the previous deliverables 1.2.1 and 1.3.1
An overview of the document is given followed by chapters on; the state chart tool for game design; the implementation of events and the object model (ECO); the class hierarchy for game development.

Document Identifier	`MOONLIGHT` Deliverable 1.5.1
Document Status	ACCEPTED
Created	14 February 1995
Revised	31 March 1995
Distribution	PUBLIC

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Chapter 1

Document Summary

1.1 Introduction

This chapter gives an overview of the document. It explains the relationship to the earlier deliverable [57] and to the other design documents that have been produced since then.

This document is divided into 3 main chapters each one describing one of the 3 main components of `VOID`, namely the statechart tool - used in high level game design - the class hierarchy - which provides both libraries and standard classes and ECOlib - the library which implements the novel `MOONLIGHT` object model. A brief introduction to each chapter is given below.

Since the delivery of the last document [57] much work has been done on progressing the design of `VOID`. Two major documents were produced after detailed consultation with the other partners. One progressed the design of the statechart notation and the other the object model. The important sections of these documents are incorporated into this deliverable in order that it can stand as comprehensive design and specification document in its own right. The sections in question are §2.2 and §2.3 and appendix C.

Appendix A contains the full specification of the current `VOID` libraries in the form of C++ header files.

In order that progress not be delayed while waiting upon the completion of ECOlib - the implementation of the object model - a simplified single node no frills ECO simulator has been written and is in current use in application development. ECOsim is described in appendix B

The following sections introduce the main chapters of the report.

1.2 The Entity Editor

The Entity Editor, referred to as the Entity Behaviour Definition Tool in the previous deliverable, is a tool for specifying Entity classes using statechart notation. An Entity is simply a high level abstraction of an object. Entities exist in event based object models, such as that provided by C++/ECO.

The most significant difficulty in designing a notation to describe entity behaviour is achieving a balance between its expressive power and its simplicity. The ideal notation would allow a designer, with minimal programming skills, to quickly specify the behaviour of an entity at a high level. Statecharts were chosen as the basic mechanism for describing behaviour. The state machine triggers the execution of actions, which must be coded by the user.

The general structure of the Entity Editor is presented in figure 2.1. As statecharts are graphical in nature, a Graphical User Interface (GUI) is required. Statecharts are somewhere between drawings and programs, so the GUI should adopt many of the standards set by typical drawing programs and integrated compilers.

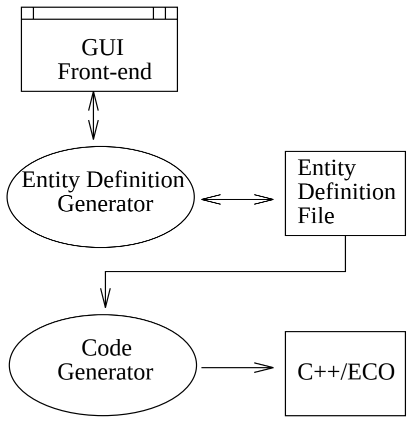


Figure 1.1: General structure of the Entity Editor.

The Entity Definition Generator drives the GUI, and allows the user to create and edit the Entities and their statecharts. It is also capable of saving and loading Entity classes, in the form of an Entity Definition File (EDF). This is purely a storage format, and is not intended to be used for execution purposes.

To allow the Entity Editor to produce executable code, the EDF is read into a Code Generator, which outputs compilable source code. While it would be desirable to make the whole process language independent, initial designs only consider the C++/ECO case. This code can then be compiled, linked and executed in the VOID execution environment.

It is commonly accepted that design and implementation occur in cycles. Initial implementation of these proposals may result in changes to the design.

1.3 Implementing the Object Model

In the ECO model [1] objects communicate among themselves using events and constraints. An **event** represents something that can happen, and it has name and zero or more parameters. The name of an event allows the objects to refer to a specific event among all the events. The parameters of an event have type (e.g., an integer or a character string). For the specific occurrence of an event the parameters are instantiated with values. These values, together with the event name, describe to the objects what happened, i.e., describe the specific occurrence of an event[2].

An **object** encapsulates some data and some processing. An object can tell other objects about something that happened, and it can react if it is told by other objects that something happened. The former is accomplished by *announcing* an event, and the latter by binding a method of the object to the required event. This binding can be dynamic, i.e., it is allowed to unbind a method from an event. The same method can be bound to several events, and the same event can have several methods (of the same or of different objects) bound to it. A binding can be established only if the signatures of the event and of the method match (if they have the same number of parameters, and the types of the corresponding parameters are the same).

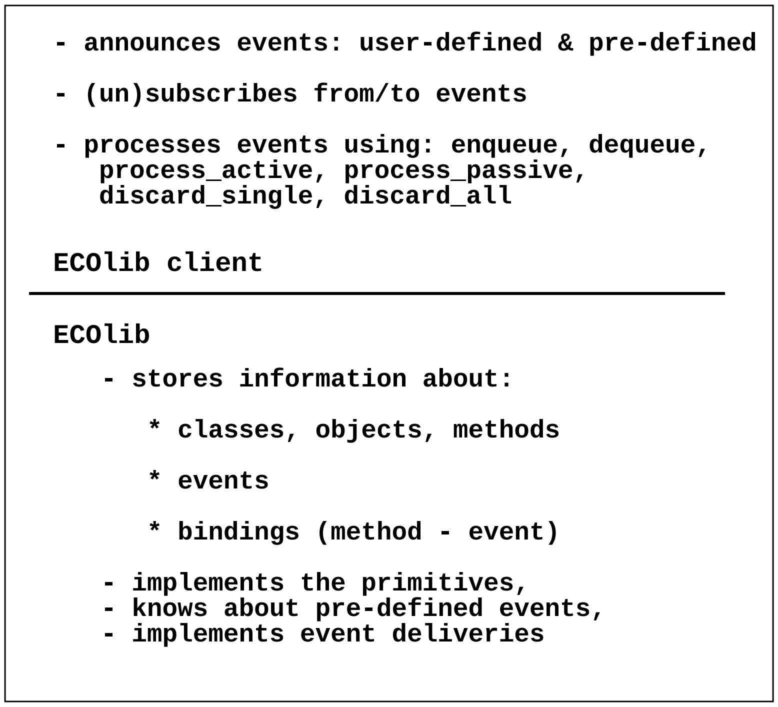
Constraints enable more flexible event-method bindings and more flexible processing of event notifications. An object may conditionally be interested in some event: it is interested only if the specific event parameter has a specific value or any value from a range of values when the event is announced. This can be expressed using the so called *Notify constraints*. In addition to this,

[1] A fuller description of the model is given in appendix C.

[2] In the following text we use "event" for both an event and an event occurrence. The context will indicate the correct interpretation.

an object may decide, based on the object's local state when it is told about an event, that the processing of the event should be postponed or even cancelled.

The ECOlib library implements a low-level runtime support for the events constraints and objects. It maintains information about classes, objects, events and their occurrences, and information about various bindings. It knows about a number of *predefined events*. The library itself uses events. More about the ECO model, and a programming language syntax for this model, can be found in Appendix C. The separation of functionality between the ECOlib and its client is shown in Figure 3.1.



```
- announces events: user-defined & pre-defined

- (un)subscribes from/to events

- processes events using: enqueue, dequeue,
   process_active, process_passive,
   discard_single, discard_all

ECOlib client
_____________________________________________

ECOlib
    - stores information about:

       * classes, objects, methods

       * events

       * bindings (method - event)

    - implements the primitives,
    - knows about pre-defined events,
    - implements event deliveries
```

Figure 1.2: Separation of functionality between the ECOlib and ECOlib client code.

1.4 The `VOID` Libraries

The VOID libraries are a a key part of the **`MOONLIGHT`** strategy for improving productivity in the development of video-game and virtual world programs. The libraries provide a unified and consistent interface to the various kinds of functionality that are required, such as two and three dimensional graphics, input control, detection of collision between entities in the virtual world and so on.

The libraries are one of three parts to the unified solution that TCD is proposing, the other parts being:

- an Entity Editor tool capable of automatic generation of application code from a graphical notation (statecharts);
- run-time support, called ECO, for event-based programming.

In the text below we describe the relationship between the VOID libraries and these other components.

Relationship to Entity Editor One of the key points in our approach to rapid prototyping of video games and virtual worlds is the use of a graphical notation to specify the behaviour of the entities. The VOID libraries are the key to allowing these specifications to become prototypes: they provide the code that is used to provide functionality for entities. By framing the various underlying software packages (such as GUL) in a consistent, object-oriented C++ library the Entity Editor tool will be able produce *working* programs *automatically*.

Relationship to ECO The VOID libraries are basically independent of (but compatible with) the ECO library, at least in this initial release. In effect the VOID libraries and the ECOlib form twin supports for the Entity Editor. This is because programs written using statecharts need the event support provided by the ECOlib. If these event-based programs are video-games then they will also require the functionality provided by the VOID libraries.

Relationship to ECOsim In this release of the libraries we include a library called ECOsim, which contains some simple class-based support for event-based programming. The purpose of this library is to allow development of programs using the libraries in advance of completion of the ECO model.

The class support is neither particularly efficient nor fully-featured, but it does offer a significant advantage over programming in straight C++: namely that it is *not* straight C++. Programs written using the standard models of invocation and named addressing of C++ will have a very different structure to those developed using events. Therefore, if code developed using the early versions of the libraries is to be of any use subsequently it should be developed using an event-based approach.

Chapter 2

Entity Editor Interfaces

2.1 Introduction

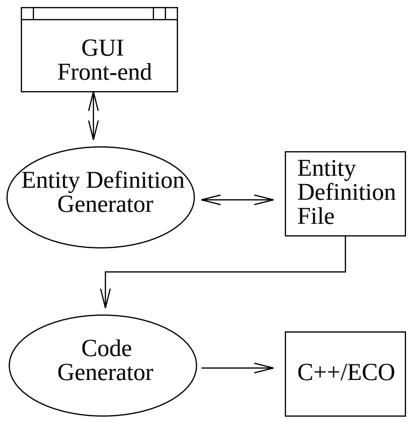


Figure 2.1: General structure of the Entity Editor.

The Entity Editor is a tool for specifying Entity classes using statechart notation. An Entity is simply a high level abstraction of an object. Entities exist in event based object models, such as that provided by C++/ECO.

The most significant difficulty in designing a notation to describe entity behaviour is achieving a balance between its expressive power and its simplicity. The ideal notation would allow a designer, with minimal programming skills, to quickly specify the behaviour of an entity at a high level. Statecharts were chosen as the basic mechanism for describing behaviour. The state machine triggers the execution of actions, which must be coded by the user.

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2.2 Entities

The following is a discussion of the concepts underpinning the MOONLIGHT entity.

2.2.1 Objects and Entities

One should be aware of the distinction between the *objects* of the MOONLIGHT object model and the *entities* defined by the MOONLIGHT Entity Editor using the statechart notation.

The object model is a relatively low level abstraction, and deals with the problem of supporting a system with many *objects* communicating with one another by raising events. Just as C++ provides an underlying model that supports C++ objects and message passing, the MOONLIGHT object model supports MOONLIGHT objects and event raising.

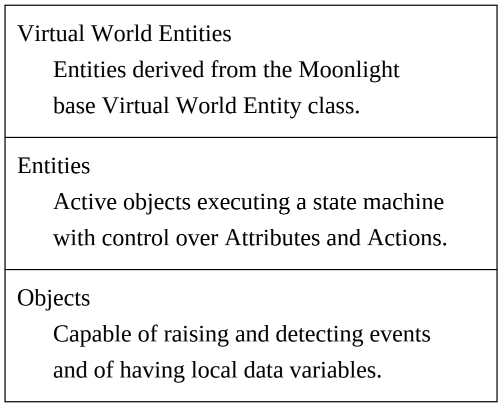
Just as one can write programs in C++, one will be able to write programs using the MOONLIGHT object model. However, both these programming paradigms are relatively low level.

To build up to a higher level, the concept of an *entity* is introduced. These are similar to objects, but support more advanced programming mechanisms.

Consider the typical process of converting a C program into an executable image. The C is first compiled into assembly language, which is in turn assembled into an executable program. C is very different from assembly language, however the compiler establishes a mapping from one to the other.

Similarly the MOONLIGHT Entity Editor should establish a mapping from the high level description of an *entity* to the lower level concept of a MOONLIGHT *object*. In theory it should be possible for the Entity Editor to produce code for any object model that supports events. So in the initial design of the notation, only a limited number of assumptions are made about the underlying object model.

The essential point is that entities are higher level abstractions than objects, which are easier to work with. The user need not be concerned with the fact that entities are implemented as objects. Similarly, it is possible to think in terms of objects, and ignore the concept of an entity altogether - one would simply be programming at a lower level.



Virtual World Entities
Entities derived from the Moonlight base Virtual World Entity class.

Entities
Active objects executing a state machine with control over Attributes and Actions.

Objects
Capable of raising and detecting events and of having local data variables.

Figure 2.2: Levels of abstraction.

2.2.2 Virtual World Entities

As described in the previous section, entities are a high level abstraction of objects. However, there are some basic similarities between the two. Just as there are classes and instances of objects, there are classes and instances of entities. The Entity Editor will produce descriptions of entity classes, from which the VOID execution environment will create instances. In other words, the principles of the entity-oriented paradigm are similar to the principles of the object-oriented paradigm.

Another similarity is the presence of inheritance. Entity classes can be derived from other entity classes. For the purposes of VOID, a standard entity class hierarchy will be provided for use by the game developer. One particular entity class will provide the basic facility of existence in the Virtual World. Entity classes derived from this class will be considered as *Virtual World Entity classes*.

For example, one may define a score-keeping entity, which simply counts the number of aliens the player destroys. Such an entity does not exist in the Virtual World, and so its class is not derived from the base Virtual World Entity class. It is simply an ordinary entity, that is acting as a counter. However, the player and the alien entities do exist in the Virtual World, and so their entity classes are derived from the base Virtual World Entity class.

So we now have the concept of an *object*, of an *entity* and of a special type of entity known as a *Virtual World entity* (see Figure 2.2).

2.2.3 Assumptions about the Object Model

The underlying system is considered to be composed of objects capable of raising parameterised events and responding to events generated by themselves or other objects. An object simply declares interest in certain events, and the object environment guarantees it will be informed whenever they are raised. If an object wishes to raise an event, it does not need to have any knowledge of those objects that have registered interest in the event (see Figure 2.3). This is in contrast to the traditional object model that requires an object to send messages to objects of which it has direct knowledge.

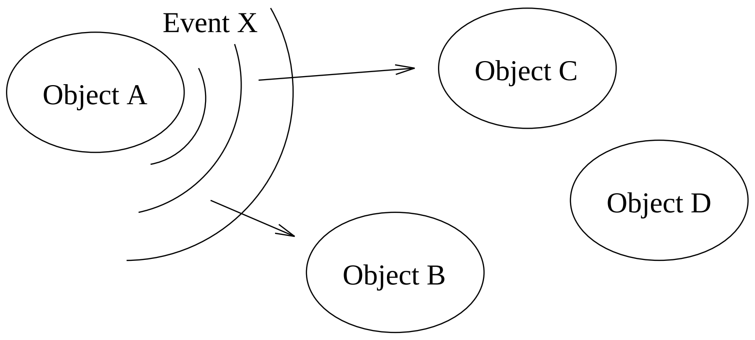


Figure 2.3: Object broadcasting event.

The objects are instances of classes. Just as in C++, a class is simply a description of the local data and methods of the objects that will be instantiated from the class. However, unlike C++, the methods are conceptually invoked when an event is raised, and not when a message is passed specifically to the object.

2.2.4 Entity Structure

Entities have four conceptual components (see Figure 2.4):

- Attributes, which contains the entity's user-definable variables.

- Actions, which can update attributes and raise events.
- State machine, which maintains the objects state and deals with the processing of events and state transitions. It is made up of the statechart logic and the state variables.
- Event queue, which holds a sequenced list of events the object has declared an interest in, and that have been raised.

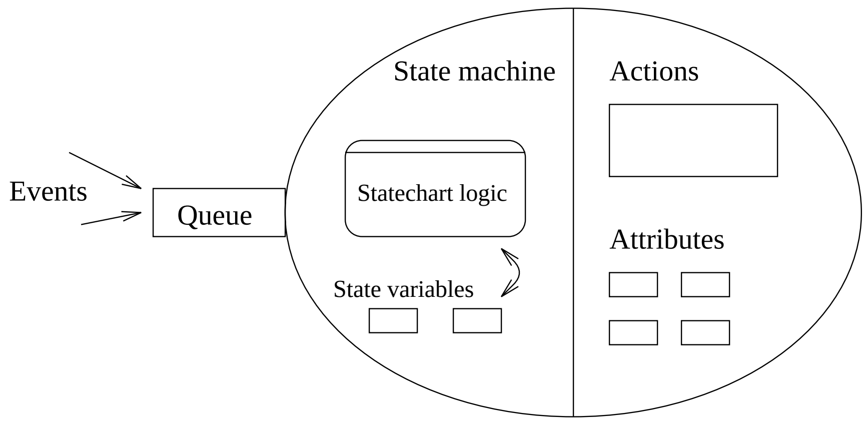


Figure 2.4: Conceptual internals of an entity.

2.2.4.1 Attributes

Attributes are variables that are private to an entity. They are defined by the user and can be used just as a C++ programmer would use variables defined in a C++ class. If an entity class is defined as having three Attributes (say `Colour`, `XPosition` and `YPosition`), then all instances of that class will have these three attributes. Their current values are independent of the state of the statechart.

2.2.4.2 Actions

An Action can perform a sequence of basic instructions; namely, the assignment of values to the attributes of the entity and the raising of events. The only values available to the script are the entity's attributes, the parameters of the action and the current state of the state machine.

In practice it is envisaged that the action will be a fragment of code of the underlying object model language (in this case C++/ECO), and so all the standard constructs it supports will be available.

Ideally though, it would be desirable to constrain the user to perform only assignment and event raising. This would ensure that all the constructs for looping and conditional execution would be represented by the statechart and not in the code of the actions.

In practise, two types of actions exist: *named* and *direct*. A direct Action is simply a fragment of code which is associated with a transition between two states in the State machine. Such actions are imbedded within the state machine. A named Action is much like a function. It is a fragment of code with a name, which can be invoked from anywhere that the action is in scope.

2.2.4.3 State Machine

An entity's state machine is described by statecharts, the syntax of which will be examined later. For the moment, consider it to be a standard state machine. In any given state, the entity is interested in a particular set of events. The arrival of these events cause transitions to new states, which might be concerned with a different set of events.

Just as a traditional state machine determines whether a sequence of inputs is valid for that particular machine (or more exactly, the language the machine is interpreting), event driven statecharts determine valid sequences of events that the object can deal with. This is why our model uses a queue to sequence the events.

The operation of the state machine is as follows: Once an event is detected at the head of the event queue, a list is made of the state changes that it triggers. The event is then removed from the head of the queue and the state changes are executed.

If it happens that the new state is not interested in the next event on the queue, then that event simply causes no state changes, and is discarded. This is reasonable when one considers that the basic purpose of the statechart is to describe valid sequences of events.

The state variables simply store the current state of the state machine. These variables are quite different in nature to the attributes described above. The attributes are defined explicitly by the user, and are updated explicitly by the execution of actions. The state variables are defined implicitly by the Entity Editor, depending on the statechart drawn by the user. While they are visible to the user (to see the current state of the entity) they are modified exclusively by the state machine of the entity when transitions occur.

2.2.4.4 Queue

As mentioned already, the state machine determines a valid sequence of events to which the entity can respond. Ideally, it would be possible to respond to each event instantaneously, and so no queueing of events would be needed. However, since an event may trigger any number of actions, each taking an indeterminant length of time to execute, the notification of other events must be queued while these actions are executing.

2.2.5 Entity Operation

The users perception of an entity is that it has a single thread of execution, which is constantly waiting for the arrival of a relevant event. Once such an event arrives, the thread wakes up, causes some state transition in the state machine, and possibly executes some actions as dictated by the transitions. When the actions are finished, the thread goes back to waiting for another event. As already mentioned, the arrival of events is queued, so no event is missed or lost as a result of executing some action while it arrived.

In effect the thread is executing a state machine whose inputs are events and whose outputs are a sequence of actions to be executed. The fact that the same thread executes the state machine as executes the actions means that no queued events are processed until the actions triggered by the last event have been executed to completion.

2.2.6 Example Entity

Consider a very simple entity, as in Figure 2.5. This entity models the idea that a computer is either 'up' (working okay), or is 'down' (has been switched off). In addition, it keeps a count as to the number of times that the computer has been 'booted up' (turned on).

The designer of this entity would have specified the simple statechart; defined the attribute `boots` (the counter); and entered the code for the action `Bootup`. The Entity Editor would then have examined the statechart and determined that one state variable, `computer`, which can hold the value `Up` or `Down`, is required to hold the current state of the entity.

The statechart is like a map. It does not hold the current state, but it does dictate what state transitions can occur, and what Actions they should trigger. It is the state variables that hold the current state.

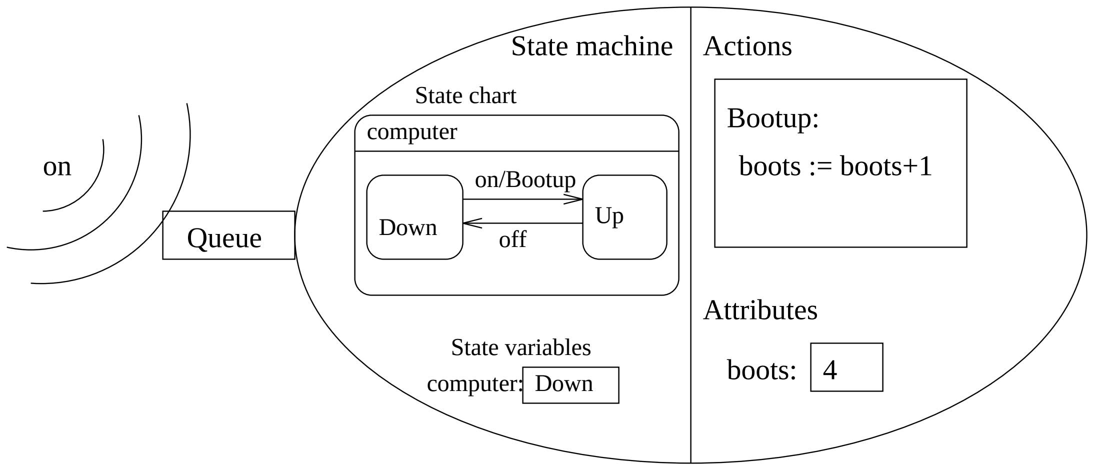


Figure 2.5: Example 'Computer' Entity.

In the example, the state machine is in state `Down` and some other entity has just raised the event `on`. The statechart indicates that in this situation the state should change to `Up` and action `Bootup` should be executed. This increments the value of `boots`. So as a result of an event the state of the entity is updated and an action is executed.

2.2.7 State Based vs Attribute Based

Note that the state of the state machine and the value of the attributes are quite independent of one another. This means that our statechart model of an entity is state based, rather than attribute based.

In other words, when an entity is in a particular state, it says nothing about the values of the attributes. In effect, the states have no formal meaning, other than to indicate that some set of events can be accepted at this point in the life cycle of the entity.

However, from an intuitive point of view, a state can have significant meaning. The simple fact that each state has a name means that a statechart can give a very good picture of what it does.

But briefly consider the merits of an attribute based system: If the notation allowed the user to specify that in one state $(x < 10)$ is true, and in another state $(x >= 10)$ is true; then transitions between states would occur depending on the value of x. However, while this may be a useful facility in many situations it introduces data dependencies on state transitions. These would be too time consuming to maintain in a soft real time environment, and so will not be supported.

2.3 Statechart Notation

This section describes the notation used in VOID to specify the state machine of an entity class. Remember that the responsibility of the state machine is to specify what events trigger what actions at each of the intuitive states of the entity's life cycle. The states have no formal meaning in the context of the attributes of the entity.

2.3.1 Statecharts

The notation used by entities to represent their state machine is that of *Statecharts*, first introduced by David Harel in 1987 [32]. Harel lists the following advantages that statecharts have over their more primitive cousins, State Transition Diagrams. Central to the criticism is the argument that STDs do not scale well.

- State diagrams are "flat". They provide no natural notion of depth, hierarchy, or modularity, and therefore do not support stepwise, top-down or bottom-up development.
- State diagrams are uneconomical when it comes to transitions. An event that causes the same transition from a large number of states, such as a high-level interrupt, must be attached to each of them separately resulting in an unnecessary multitude of arrows.
- States diagrams are extremely uneconomical when it comes to the number of states required, especially if a separate state is used to represent each value that a variable can take on.

  As the system under description grows linearly, the number of states grows exponentially, and the conventional FSM formalism forces one to explicitly represent them all.
- Finally, state diagrams are inherently sequential in nature and do not cater for concurrency in a natural way.

Harel goes on to describe statecharts as:

$$\textit{statecharts} = \textit{state diagrams} + \textit{depth} + \textit{orthogonality} + \textit{broadcast communication} \qquad (2.1)$$

Graphically, states are represented by rectangles with rounded edges. If a state has sub-states, then a horizontal line divides the rectangle into two sections, one for the state's name and one for the representation of its sub-states.

Transitions have a start state and an end state (which may be one and the same) and are denoted by an arrow connecting two states.

Within a given entity class, all state names must be unique. This restriction does not apply to transitions, which are labelled with the event and action that apply to it.

2.3.2 Depth

The primary addition to STDs that statecharts provide is to allow states to possess sub-states with an *XOR* relationship. This enables groups of transitions in a STD, triggered by the same event, to be specified with a single transition in the corresponding statechart as illustrated in following two diagrams.

The internal transitions obey an *exclusive-or* rule: thus in Figure 2.7 being in state **P** means being in *either* state **A, B or C** but excludes being in more than one of them at once.

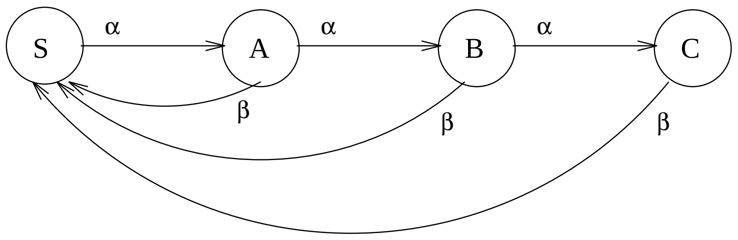


Figure 2.6: Replicated transitions in an STD

2.3.3 Orthogonality

The second improvement that statecharts bring to STDs is the ability to separate aspects of state that have no inter-dependency. This prevents the combinatorial explosion of states that occurs with STDs.

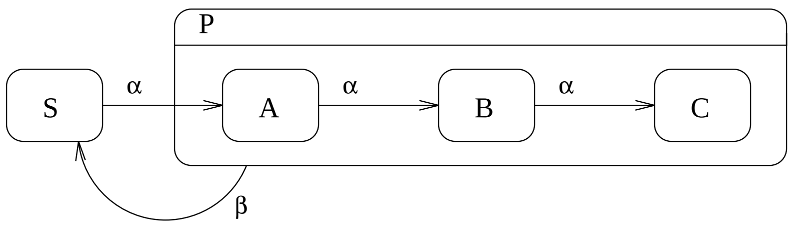


Figure 2.7: Statechart showing elimination of replicated transitions

The notation used is a dotted line partitioning a state into two orthogonal child-states. The parent is then said to be in *both* of these child-states, hence this is known as an *AND decomposition*.

Again, two diagrams (Figures 2.8 and 2.9) serve to show the advantage that this notation has over the conventional STD, even for relatively small machines. The **A** and **B** states have been separate into the orthogonal state **Q**, and the **X**, **Y** and **Z** states have been separated into state **R**.

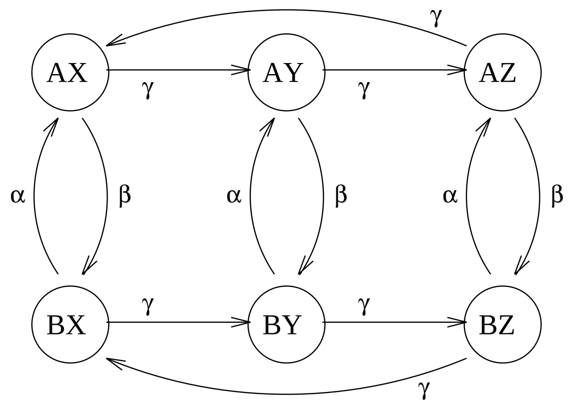


Figure 2.8: STD with implied orthogonal states

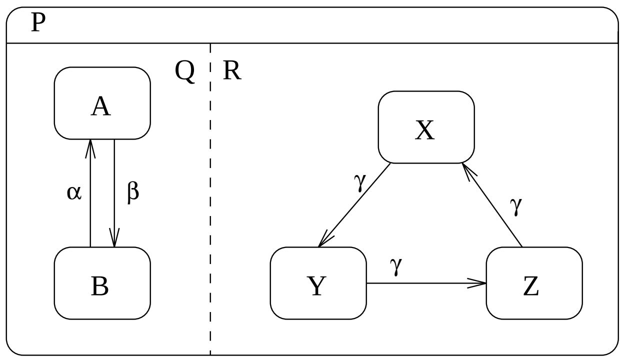


Figure 2.9: Statechart with orthogonal states

2.3.4 Broadcast Communication

Statecharts do not limit the one to many nature of events as a communication mechanism. An event is sent to all interested parties both within the orthogonal states of a statechart and outside to other entities.

2.3.5 State Transitions

A state transition is a uni-directional path linking two states. It represents a potential change from one state to another. The syntax of the annotations on the arrow of a transition are as follows:

`Event(Event-Parameters)[Constraint]/Action(Action-Parameters)`

Some examples are presented in Figure 2.10. The top example shows the general syntax. The next example indicates that there is a transition from left to right when the `Quit` event is detected. The next shows a parameterised event `Add(n)` triggering action `Increment` if the constraint `[n==1]` is true. The final example shows a transition which invokes action `MoveLeft(1)` when event `JoystickLeft` is detected.

All transitions from a stable state must be triggered by an event. The event parameters are optional, depending on whether the event supports them. The optional constraint expression is a function of the attributes, state variables and the event parameters. The optional action is executed whenever the transition is traversed.

A transition is said to be active if the following are true:

- The state machine is in the source state of the transition.
- The event that triggers the transition is at the head of the entity's event queue.
- The constraint evaluates to true.

Once all the active transitions within the state machine have been identified, the event is removed from the head of the queue.

Then, for each state that has an active transition leaving it, the associated action is executed; the source state is left; and the destination state is entered.

Note, if event parameters were to be mapped directly to action parameters, there would be the limitation that only certain actions could be triggered by certain events.

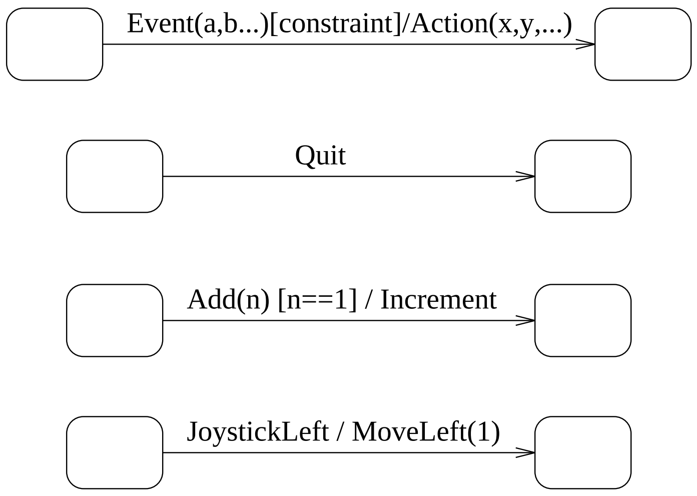

Event(a,b...)[constraint]/Action(x,y,...)
Quit
Add(n) [n==1] / Increment
JoystickLeft / MoveLeft(1)

Figure 2.10: Examples of annotated transitions.

2.3.6 Unstable States

In order to allow sequencing, iteration and conditional execution of actions in response to a single event, the concept of the *unstable state* is introduced. This is a state which is left the moment it is entered. None of the transitions leaving it can be dependent on the raising of an event. The notation uses a diamond within a state box to indicate that it is unstable. While the transitions are not triggered by events, constraints can still be applied, and actions can still be triggered.

To force at least one transition to be active when in the unstable state, each unstable state must have one completely unconstrained transition leaving it. This transition is only taken when no other transition is active.

The simplest use of an unstable state is to ensure the sequencing of actions in response to an event (see Figure 2.11). Here α triggers **Action1**, followed by **Action2**.

The unstable state also allows for the conditional movement from one state to one of many other states in response to a single event (see Figure 2.12). Iteration is also possible, though this introduces the possibility of infinite loops (see Figure 2.13). Note that in this example there are two transitions from state **T** to state **B**. One gives the specific exit condition for the loop, and the other is the required unguarded transition for the unstable state. The guarded transition is redundant in this case.

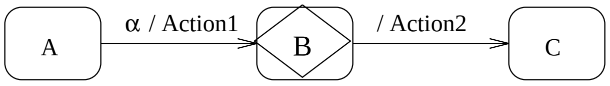


Figure 2.11: Single Event triggering sequence of actions using unstable states.

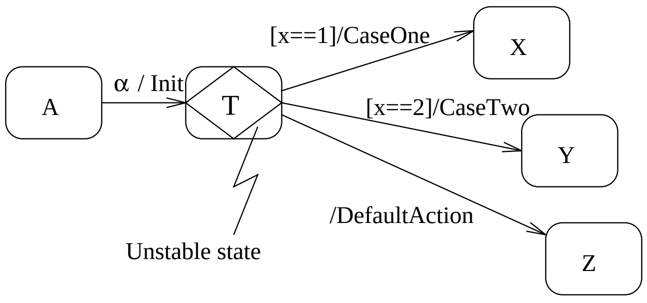


Figure 2.12: Selection implemented using an unstable state.

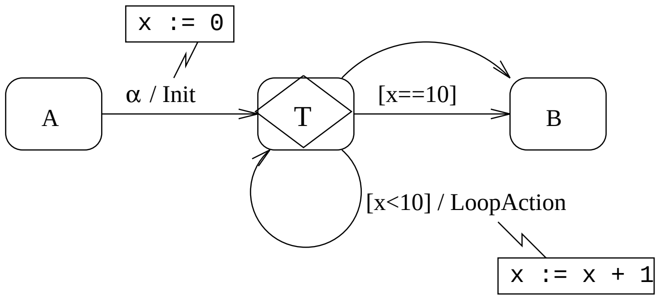


Figure 2.13: Iteration implemented using an unstable state.

2.3.7 Non-determinism of Transitions

As with STDs, statecharts can have sets of transitions that are non-deterministic. For statecharts Lucas [39] describes three categories: pure non-determinism, potential non-determinism and apparent non-determinism.

Pure Non-determinism This is identical to non-determinism in a State Transition Diagram: from one state there are two transitions with different destination states (as in Figure 2.14), and both occur as a result of the same event. It is thus arbitrary which is taken.

Potential Non-determinism In this case the two transitions are conditional: hence there is non-determinism only if both conditions are true. (See Figure 2.15)

Apparent Non-determinism This case is illustrated by the two transitions triggered by event α in Figure 2.16. Lucas specifies "outermost" first semantics in this case, so the result is actually deterministic and is a transition to child-state **Y**. This approach preserves the "black box" nature of state **P** and so is preferable. (See Figure 2.16)

The MOONLIGHT approach to non-deterministic state transitions is as follows: If a state has more than one active transition as a result of an event notification, then one of the active transitions is chosen arbitrarily as the transition to follow. This applies for both pure and potential non-determinism.

The argument for this stance is that a statechart containing non-determinism is badly specified. Obviously it would be desirable to warn the user if they specify such a statechart, but this may not always be possible - especially in the case of potential non-determinism. The problem is placed in the hands of the user of the Entity Editor.

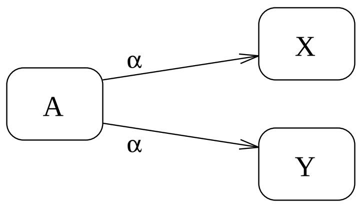


Figure 2.14: Pure Non-determinism.

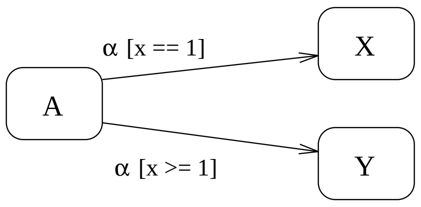


Figure 2.15: Potential Non-determinism.

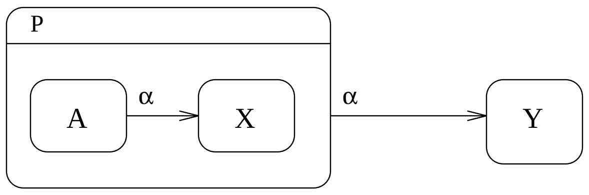


Figure 2.16: Apparent Non-determinism.

2.3.8 Non-determinism of Execution Order

The user perceives the entity as being maintained by a single thread of execution. In a situation where an event triggers more than one action (see Figure 2.17) these actions are perceived as executing sequentially rather than concurrently.

This is desirable, as we wish to shelter the user of the Entity Editor from the complexities of concurrency. In the example, the perception will be that either **ActionF** followed by **ActionG** was executed, or that **ActionG** followed by **ActionF** was executed. The order of execution of actions triggered by a single event is non-deterministic.

Consider another example (See Figure 2.18): If the current state is $\{\mathbf{A},\mathbf{X}\}$ then α will trigger four actions. However, the only facts that can be declared about the order of their execution are that **ActionD** will occur before **ActionE**; and **ActionF** will occur before **ActionG**.

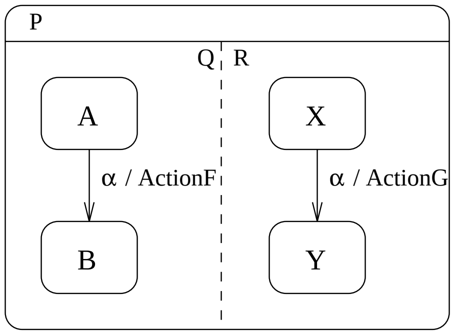


Figure 2.17: Non-deterministic execution order of Actions.

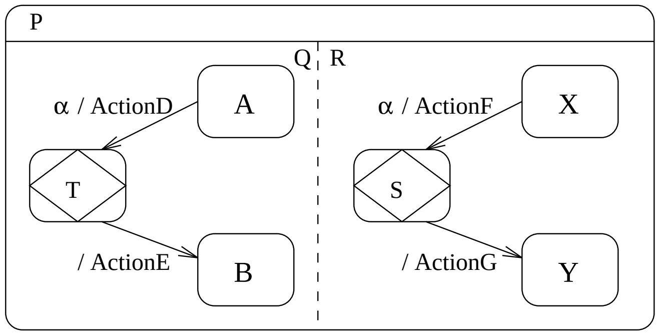


Figure 2.18: Non-deterministic execution order with unstable states.

2.3.9 Legality of State Transitions

Where transitions do not intersect with a state boundary, they are allowed (see Figure 2.19), regardless of whether the source or destination are XOR, AND or elementary states. Transitions that cross the dotted boundary of an AND state are illegal (see Figure 2.20), as it would leave one side of the boundary without an active state.

A transition can pass out of a state boundary if that state is an XOR state (see Figure 2.21), but not if it is an AND state (see Figure 2.22). This is to prevent two different transitions leaving the AND state and going to different states outside the AND state.

Transitions can pass in through a state boundary of an XOR or an AND state, overriding the default or the history (see Figure 2.23).

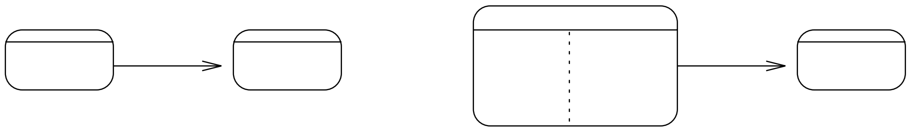


Figure 2.19: Valid transitions not crossing boundaries.

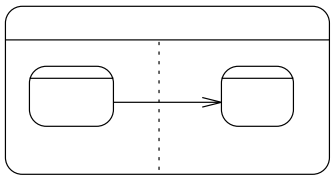


Figure 2.20: Illegal cross-AND-barrier transition.

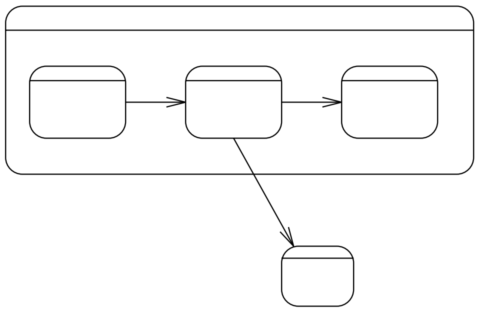


Figure 2.21: Valid outward XOR transition.

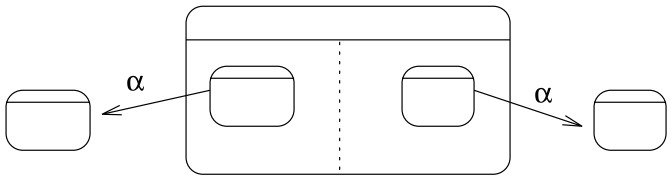


Figure 2.22: Illegal outward AND transitions.

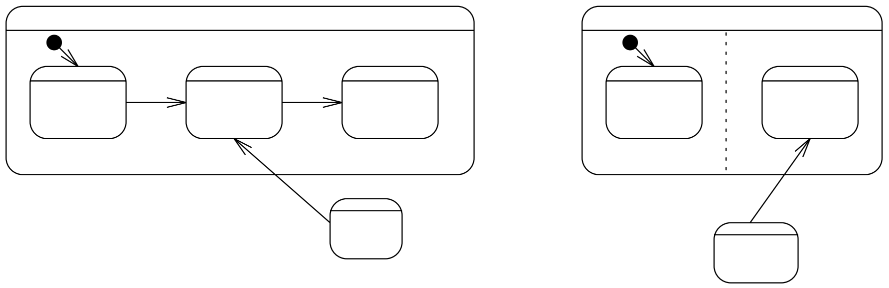


Figure 2.23: Valid inward transitions.

2.3.10 Default States

Any state which contains sub-states can be considered as a 'black box' state. Within such a state there should be an indication of which state is the default. This allows transitions to enter the black box state without having to know which particular sub-state should be entered as well.

A default state simply has a short arrow pointing from a dot to one of the internal states. In the example (see Figure 2.24), if event α occurs while in state **S** then the black box state **P** is entered, with sub-state {**A**,**X**}. However, if event β occurs, then **P** is entered with sub-state {**B**,**X**}.

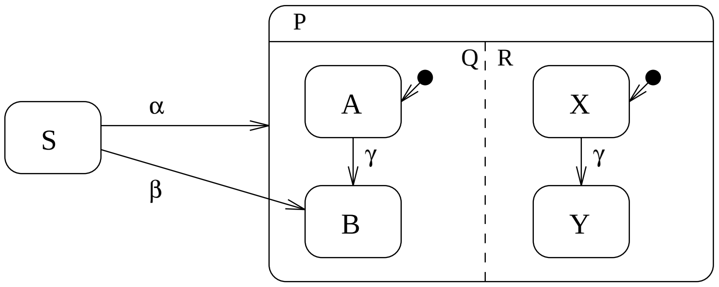


Figure 2.24: Example of default states.

2.3.11 Histories

Any state can be equipped with a history which will cause the state to re-enter its last child-state rather than the default child-state (if the state is being entered for the first time then the default will be used). Histories may be *shallow* or *deep*: the latter recursively implies a history for every sub-state within the state with the history. The two notations are shown in figure 2.25 where child-state **Q** has deep history, and **R** has shallow history.

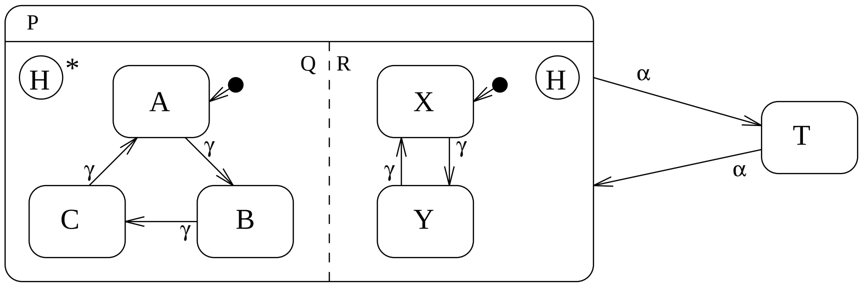


Figure 2.25: Example of history.

2.3.12 Example

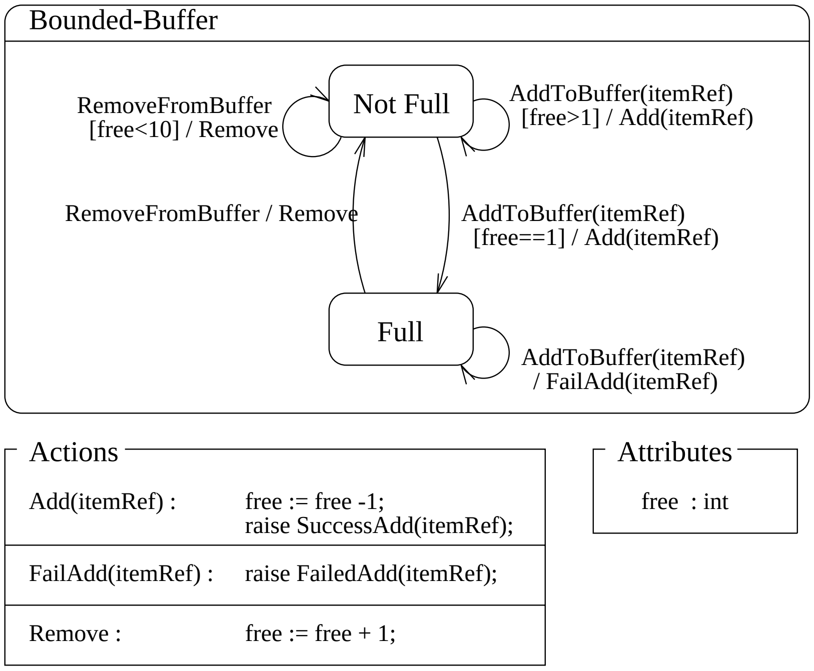
As an example of the notation, consider the following bounded buffer example: An entity is required to act as a bounded buffer, storing a fixed number of items. These items are entities themselves, who attempt to enter the buffer of their own accord. They either succeed or fail, as arbitrated by the bounded buffer entity, and are informed as such.

As can be seen from Figure 2.26 the bounded buffer Entity has two elementary states, `Not Full` and `Full`. While in the `Not Full` state, the event `AddToBuffer` is accepted and triggers the **Add(itemRef)** action. The destination state depends on which transition is followed; which in turn depends on the outcome of the constraints. The `itemRef` parameter is a unique identifier for the item entity.

The **Add** action decrements the `free` attribute, and raises a `SuccessAdd(itemRef)` event which reports back to the original item.

The item entity is expect to raise a `RemoveFromBuffer(itemRef)` event at some later time, which has the conceptual effect of removing the item from the buffer. This event is acceptable in both states of the bounded buffer entity, except when there are no items in the buffer.

An simple item entity is given in Figure 2.27. The event α triggers the `JoinBuffer` action, which raises the `AddToBuffer` event. The parameter `selfRef` is a standard value available to all entities, representing a unique entity identifier. The `Wait` state waits for the failure or success notification and moves on to the appropriate state. The constraints on these transitions ensure that the item only uses events which are intended for it, as opposed to other items. Finally, event β triggers the **LeaveBuffer** action, which sends the `RemoveFromBuffer` event to the buffer entity.


Bounded-Buffer
Not Full
RemoveFromBuffer [free<10] / Remove
AddToBuffer(itemRef) [free>1] / Add(itemRef)
RemoveFromBuffer / Remove
AddToBuffer(itemRef) [free==1] / Add(itemRef)
Full
AddToBuffer(itemRef) / FailAdd(itemRef)
Actions
Attributes
free : int

Actions	
Add(itemRef) :	free := free -1; raise SuccessAdd(itemRef);
FailAdd(itemRef) :	raise FailedAdd(itemRef);
Remove :	free := free + 1;

Figure 2.26: Example of a Bounded-Buffer entity.

2.4 Entity Editor Graphical User Interface

This section discusses the requirements of the Entity Editors' user interface by considering two things; the objectives of a user attempting to create many entity classes for a video game, and the style of interface provided by existing applications similar in nature to the Entity Editor.

A prototype user interface is proposed, detailing the layout of the windows, menus, and popups.

2.4.1 Requirements

At a basic level, the purpose of the Entity Editor is to allow the user to specify Entity classes. This includes defining statecharts, attributes, actions, events and the inheritance structure. (See Figure 2.28). Specifically, it's purpose is to specify Entity classes for use in video games and virtual worlds.

In the course of writing even the simplest of video games, the user will probably create several Entity classes. It would be useful to adopt the concept of a *project*, which references many entity

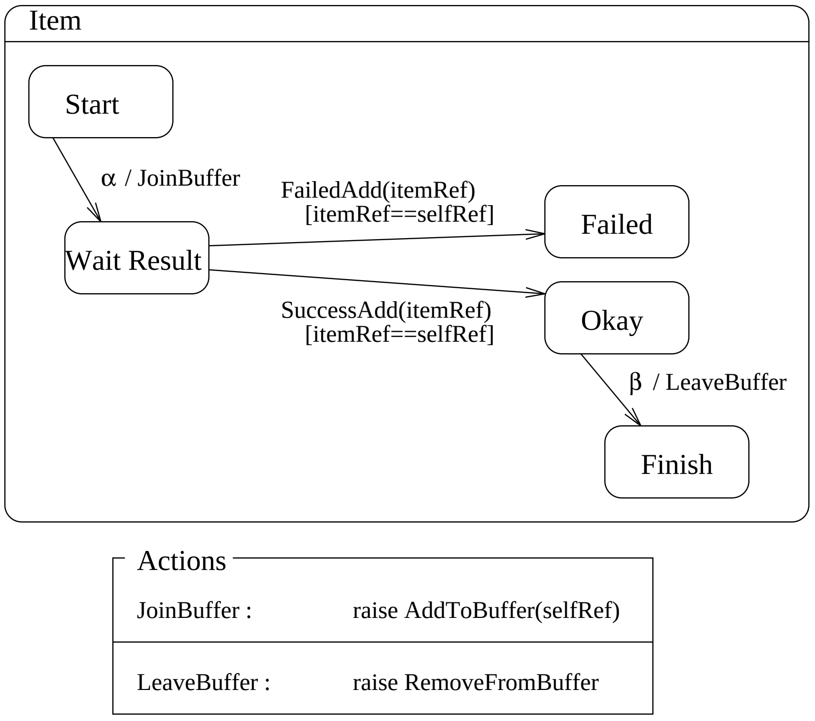

Item
Start
α / JoinBuffer
Wait Result
FailedAdd(itemRef) [itemRef==selfRef]
Failed
SuccessAdd(itemRef) [itemRef==selfRef]
Okay
β / LeaveBuffer
Finish
Actions
JoinBuffer : raise AddToBuffer(selfRef)
LeaveBuffer : raise RemoveFromBuffer

Figure 2.27: Example of a simple item entity.

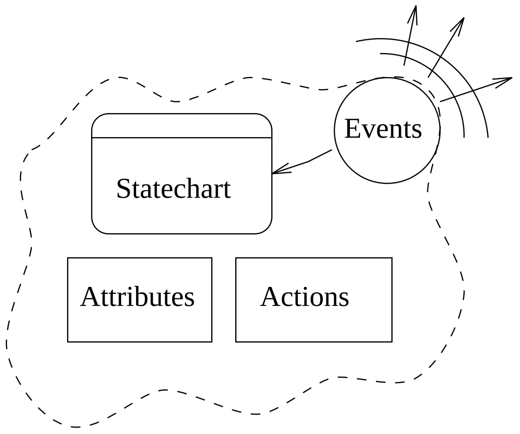


Figure 2.28: Aspects of an Entity class defined by the Entity Editor.

classes and maintains the event definitions used by the Entities. (See Figure 2.29). By opening a particular project, the user has an easy way of working with that particular set of Entities and Events. The project can have Entity classes added to it, or removed from it. One Entity class may be referenced in many different projects.

Maintaining projects could be considered ancillary to the purpose of the Entity Editor, but as it is intended as a useful tool for creating the many entities of a video game it would be best to consider these aspects of the tool early on in the design process.

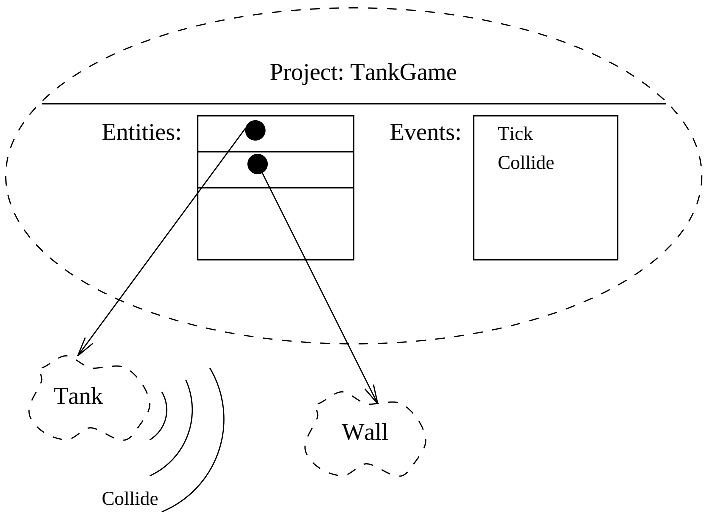


Figure 2.29: Project holding references to Entity class definitions.

2.4.2 Related Applications

Ideologically the Entity Editor falls somewhere between the modern day integrated compiler and the drawing package. The project management aspects are heavily influenced by compilers such as THINK-C on the Macintosh, Borland C++ and MS-Visual C++ on the PC (under Windows). The Entity specification aspects are more akin to a drawing package, or visual database, as found in ClarisWorks by Claris corp.

As far as possible, the design of the user interface to the Entity Editor has attempted to reflect the *look and feel* of these (and so many other) applications. While the GUI paradigm is far from standard, a number of common themes and ideas do exist.

Increasingly users *expect* certain facilities from any application that aspires to being considered GUI driven. This fact adds considerably to the work required in designing a good user interface. The pay back comes with the reduced training time for users of the application, as they are already familiar with many of the basic concepts.

2.4.3 Application Window/Screen

This is the containing workplace associated with the Entity Editor. Depending on the particular GUI, it is either an application window with menu bar (in the case of WINDOWS) or simply a new set of menus in the common menu bar (in the case of the Macintosh). Under WINDOWs, all the sub-windows opened by the application appear to be contained within the application window. In contrast, the Macintosh has no concept of an application window, and simply allows any program to place a window anywhere on the screen. The menu bar, however, changes depending on which application is active.

2.4.4 Menu bar

The Entity Editor presents one common menu bar. While this may be duplicated for each window, depending on the GUI, each will look the same (see figure 2.30). The workings of the menu bar are closely tied to the particular GUI.

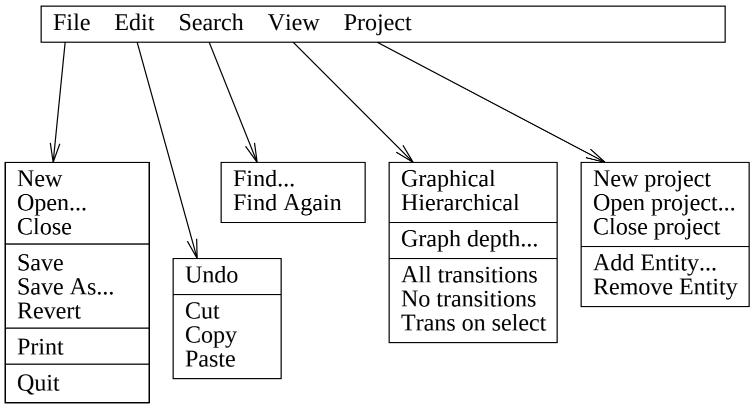


Figure 2.30: Entity Editor common menu bar.

2.4.4.1 File Menu

This menu deals with the general management of Entity windows. The **New**, **Open...** and **Close** options open a new (empty) Entity class window, load one from disk and close the current one, respectively. The **Save** and **Save As** options allow the Entity to be saved to disk. **Print** outputs the contents of the current window to the printer, and **Quit** exits the program (prompting if a save is required).

2.4.4.2 Edit Menu

The **Undo** option attempts to undo the last operation. It is not always available, but can be useful in certain situations. The **Cut**, **Copy** and **Paste** options act on the currently selected graphical or text piece, and have their usual meanings. **Cut** removes the selection and places it in the clipboard. **Copy** copies (as opposed to removes) the selection into the clipboard. **Paste** takes the contents of the clipboard and copies it to the workplace.

2.4.4.3 Search Menu

This provides two options: **Find**, which brings up a standard search window (see Figure 2.31) allowing the user to enter the requirements of the search; and **Find Again** which repeats the last search to find the next match.

The search facility allows the user to find particular Entity classes, or particular Actions or Attributes of a class. When a particular Entity window is active, then the search is automatically limited to that window (unless **All Entities** is checked). When the Project window is active, the search covers all the entities.

2.4.4.4 View Menu

The first two options affect either the Project window or the current Entity window, depending on which is active. **Graphical** changes the current window so that it displays a graphical representation of it's contents. In the case of the Project window, a horizontal class hierarchy is

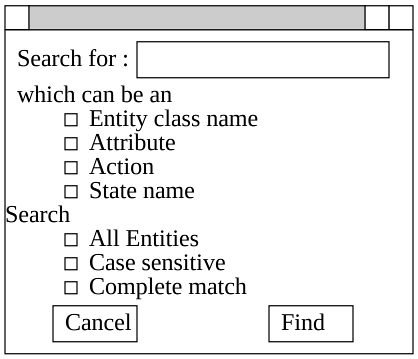


Figure 2.31: Search Window.

displayed. For the Entity window a standard statechart is shown. **Hierarchical** changes the view to a hierarchical listing of the principle items of the window. The general layout is similar for both the Project window and the Entity windows.

When the view is graphical, the **Graph depth...** option allows the user to specify how many nested levels to attempt to render. This allows the user to prevent very deep (and graphically small) sub-states being rendered. Note that regardless of the current Graph depth, if a state is graphically too small due to it's depth, it will not be rendered.

2.4.4.5 Project Menu

All project related options are placed here. The standard **New Project**, **Open Project** and **Close Project** options work in the standard way. One point to note is that only one project can be open at a time.

The **Add Entity** option allows you to add an existing entity to the project. **Remove Entity** removes the currently selected Entity from the project.

2.4.5 Project Window

There can be at most one project window open in any one instance of the Entity Editor. This window presents a view of the basic MOONLIGHT entity class hierarchy together with any user defined Entity classes added to the project (see Figure 2.32).

The class hierarchy can be represented in a graphical or hierarchical manner depending on which view is selected in the **View** menu. By double clicking on a particular Entity class in the project window, an Entity window is opened on that class.

The button bar of the project window allows new events to be defined. The entities within the project only have access to the events defined in the current project. The pointer button allows Entity classes to be moved around in the graphical view.

2.4.6 Entity Window

The Entity window allows the user to specify the statechart, attributes, actions and events used by a particular entity class. It has two viewing modes, Graphical and Hierarchical.

2.4.6.1 Graphical View

The statechart is rendered using similar notation to that described in the previous section for the graphical view (see Figure 2.33). The notational differences are purely for legibility.

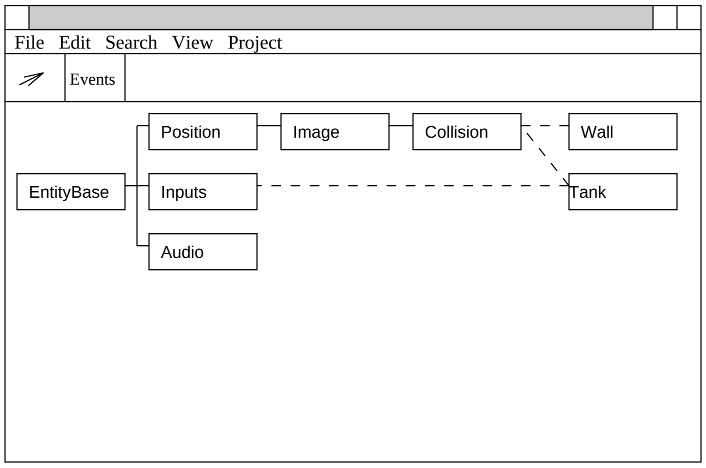


Figure 2.32: Project Window.

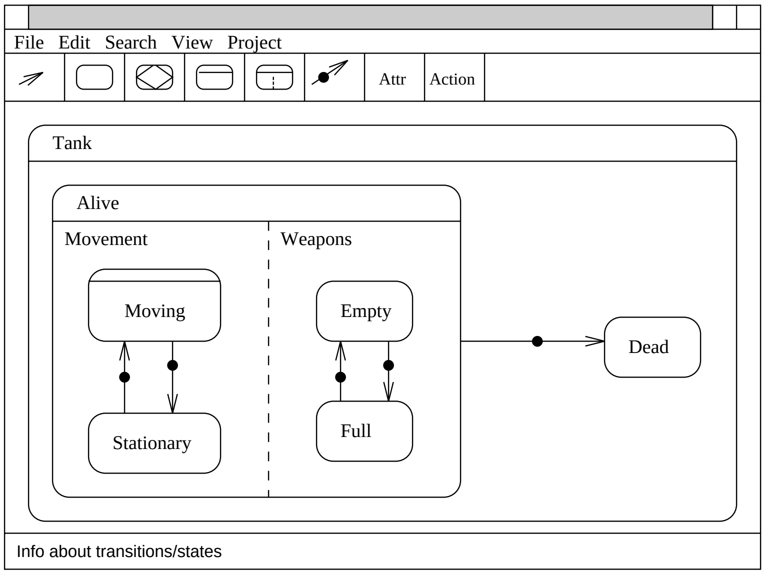


Figure 2.33: Graphical View of Entity Window.

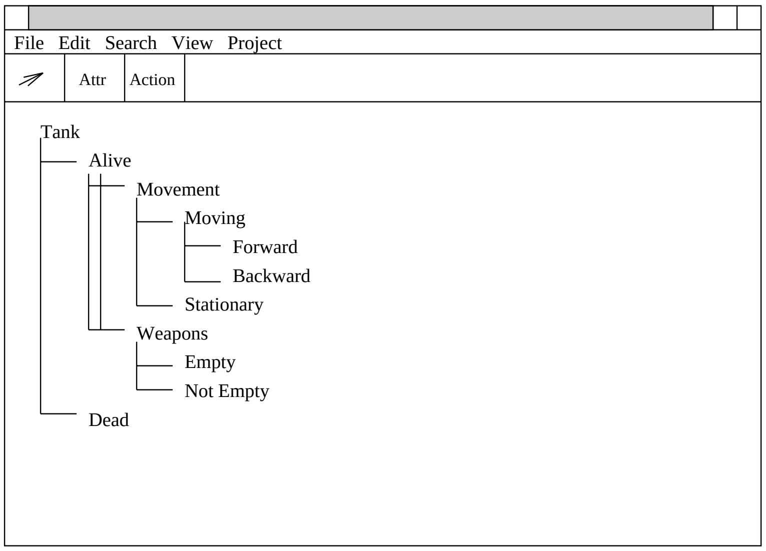


Figure 2.34: Hierarchical View of Entity Window.

XOR and AND states may not have their sub-states rendered. As significant depth in a statechart may cause the sub-states to appear very small, some XOR and AND states may be rendered in an abreviated way. Instead of the name appearing in the title bar and the sub-states appearing below the bar, the title bar is empty and the name appears below it. Two factors affect whether or not a state will be abbreviated; the current **Graph depth**, and the visible size of the rendered state.

For example, the **Moving** state in figure 2.33 is actually an XOR state with two sub-states. However, they would be too small to see, so the abreviated form is used.

Also for legibility reasons, transition annotations are not placed on the statechart diagram. Instead, they are displayed in the information panel at the bottom of the window when the pointer is over a particular transition.

The graphical view is used to create the statechart. The button bar at the top of the window has a number of icons which are used to add new states and transitions to the statechart. In addition, the states may me moved around, resized and edited.

The outermost visible with the graphical view may not be the outermost state of the whole statechart. By double clicking on the title of the outermost visible state, the view is redrawn with the parent state of that state as the outermost visible. Similarly, if a sub-state is double clicked on, it becomes the outermost visible state.

The main drawback with the graphical view is the limit as to how much information can be legibily displayed.

2.4.6.2 Hierarchical View

All statechart sub-states are shown concisely in the hierarchical view. However, no transitions are show. The states are displayed in a vertical list with sub-states placed under their parent state and indented slightly. In the case of an XOR state, a single vertical line joins the sub-states to their parent state. For AND states, two parallel lines are used (See Figure 2.34). By double clicking on any state name, the view changes to the graphical view, with that state as the outermost visible.

With the hierarchical view it is possible to see that the **Moving** state is an XOR state made up of two sub-states, **Forward** and **Backward**.

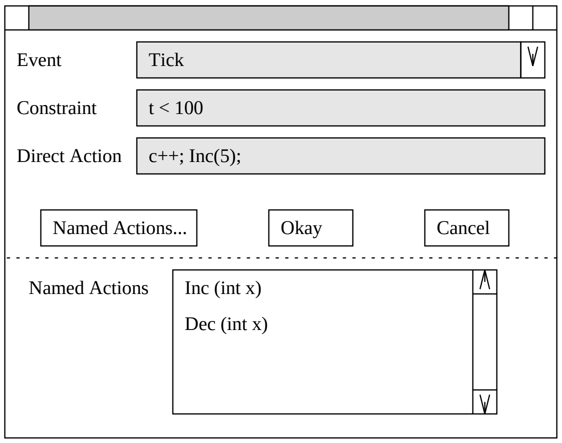
2.4.6.3 Button Bar

The button bar provides the tools to allow new states to be added to the statechart. Note that most of the facilities are only available while in the graphical view. There is a button to:

- change the pointer to the default mode of operation. That is, to drag and resize existing states;
- add a new elementary state to the statechart;
- add a new unstable state;
- add a new XOR state;
- add a new AND state;
- add a new transition;
- add an attribute to the Entity class;
- add an action to the Entity class.

The button for adding a new transition requires that the user specify the source and destination states. When this is done, a popup window opens which asks them to enter details of the event, constraint and action. The Attribute and Action buttons open pop up windows which allow details of Attributes and Actions to be added to the Entity class.

2.4.6.4 Transition Popup Window



Event: Tick

Constraint: t < 100

Direct Action: c++; Inc(5);

Named Actions: Inc (int x), Dec (int x)

Figure 2.35: Transition Popup Window.

To specify a transition from one state to another, the user first clicks on the transition button of the Entity Window, then clicks on the source and destination state. Once this has been done, the transition popup window is opened (see Figure 2.35). Here the user selects the event that is to trigger the transition from a drop-down list. If required, a constraint can be entered. This must be an expression which evaluates to zero (false) or non-zero (true), written in the syntax of the target language. In this case C++/ECO. Finally, an Action can be associated with the transition.

The general term *Action* refers to the code executed as a result of a transition from one state to another. There are two types of Actions, *direct* and *named*. **Direct Actions** are nameless fragments of code which are associated with a single transition. When the transition is taken, the code fragment is executed. There is no way to associate the same code fragment with a different transition (other than using cut and paste), as it is implemented as in-line code in the state machine.

However, there may be sets of instructions that the user wishes to invoke from many different transitions. In this case, **named Actions** can be defined (see below), which contain the frequently used code. Many transitions can then invoke the one named Action by calling it from within their direct actions. A named Action is implemented as a single method. The invocation of a named Action is actually a method invocation.

The popup initially opens without displaying the current list of named Actions. If the **Named Actions** button is clicked on, the window expands to show the list. This can be a useful reminder list for the user when they are invoking a named Action from the direct Action.

2.4.6.5 Attributes Popup Window

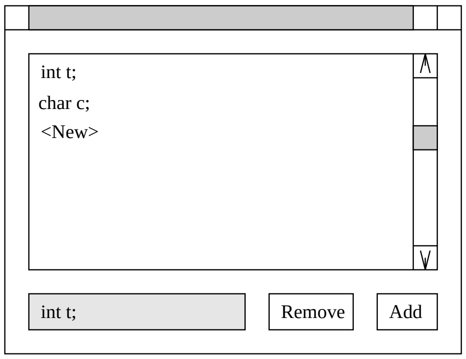


Figure 2.36: Attributes Popup Window.

The attributes popup window (see Figure 2.36) is opened by clicking on the **Attrs** button in the Entity window. From here, new attributes can be declared and existing ones edited or deleted. The declaration must be in the syntax of the target language, so in this case attributes are declared in the same way as variables in C++/ECO.

2.4.6.6 Named Actions Popup Window

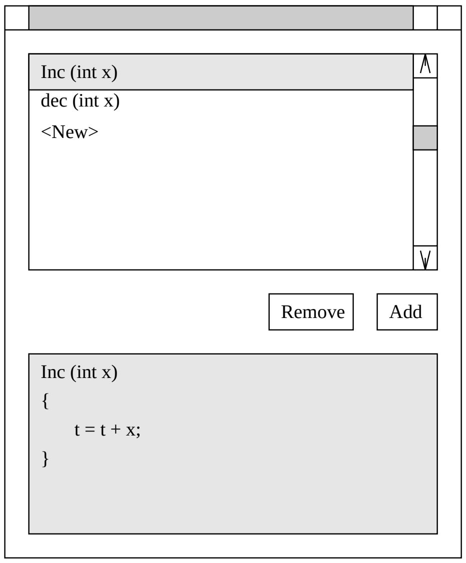
The actions popup window (see Figure 2.37) is opened by clicking on the **Actions** button in the Entity window. From here, new named Actions can be declared and existing ones edited or deleted. As discussed previously, the actions must written in the syntax of the target language. In this case, C++/ECO.

2.4.7 Summary

The Graphical User Interface presented by the Entity Editor must strive for simplicity and elegance. It must present the statechart clearly, and make it easy for the user to alter it. As the user is required to enter small fragments of code, aids should be provided to make this as simple as possible. It must also be possible to manage several Entity classes in the one project, and allow common definitions of events to pass between them.

2.5 Entity Definition File Format

From a logistic point of view, the most fundamental operations that the Entity Editor must perform are those of storing and retrieving Entity classes. Without these abilities, you can not save Entity



```
Inc (int x)
{
     t = t + x;
}
```

Figure 2.37: Actions Popup Window.

classes just created, nor can you load Entity classes created yesterday. So the requirement is two fold: To store the complete definition of an Entity class as it currently stands in the Entity Editor; and to allow the retrieval of a previously stored Entity class in such a way that the Editor window looks exactly as it did just before the storage operation.

This means that all the information about the Entity class must be written to a file in a specific format, ready for reading back in. Obviously within the Entity Editor there will be an internal representation of the Entity class in the form of the data structures used by the program. However a simplistic memory dump of memory is a very poor file format structure. An applications internal data structures should be suited to what it does best and how it does it. What is 'best' changes as an application evolves new features. But a file format should be suited to long term storage and interchange between application versions.

There is no requirement that this file format be executable in any way. While definitions of entities in this format may be used as input to the code generator, the definitions themselves can not be executed.

2.5.1 Storage requirements

For each entity class, there are a number of details which must be recorded.

- The events it generates and responds to;
- the attributes;
- the actions;
- the statechart.

The events must be detailed to help ensure that two different Entity classes use the save event in the same way. The details about each event must include its name together with the name and type of each of its parameters. The attribute names must be stored, along with their types. The action names must be stored with their code fragments, as well as the name and type of each of each of their parameters.

Finally, the hierarchical statechart must stored, together with the current graphical location and size of each state. This graphical information is superfluous in the context of the execution of the state machine. However, it is essential from the point of view of the user who wishes to arrange their statecharts in a visually convenient way.

2.5.2 File Format Philosophy

Before designing a file format to hold the details identified above, we must consider that in future versions some of these details may change, or new ones might emerge. So the storage format must be versatile enough to allow for future expansion.

For this reason a grammar based structure is proposed for the storage format, using standard ASCII characters to encode the tokens. This provides two major benefits. Firstly, the resulting Entity definitions are ASCII readable, allowing easy human examination. Secondly, a grammar can be expanded to include new language constructs by ensuring that the language the grammar describes is a superset of the old language. New versions of the Entity Editor should always be able to read old Entity files, as they will always be in a language that is just a subset of the later versions of the language.

This approach is not uncommon. Consider Adobe's PostScript or Microsofts RTF (Rich Text Format). Both are grammar based, ASCII encoded interchange formats.

2.5.3 Format Syntax

The general syntax is not unlike a typical programming language, such as C or Pascal. The overall order of declarations is: events; attributes; actions; and finally a single state definition which contains all the states of the Entity as sub-states.

The declaration of an event includes the events name (a standard alphanumeric identifier) and its parameters. For example

```
event Time (msecs : int);
```

declares an event called 'Time' which has one integer parameter, the current system time in milliseconds. This event might be raised by a clock entity every few milliseonds, and might be subscribed to by entities interested in knowing the current time.

A typical Entity class would have many event declarations. No distinction is drawn between those events that are generated and those that are received. These declarations simply allowing the Entity Editor to perform basic type checking on the use of the events.

The attributes are declared as small code fragments which declare the appropriate variable. Consider

```
attribute [[int xposition;]]
attribute [[int yposition;]]
```

which declares two attributes of type integer.

Named Actions are defined by providing the action name; its parameters; and the associated code fragment. For the moment, this code fragment must be in the target language, C++/ECO. Ideally this would be a generic language, which could be converted into the particular syntax of the underlying language. This would have to be the case if the Entity Editor were to be completely language independent. In the following example everything between the [[and]] will be pasted into the resulting Entity code.

```
action [[
  IncEnergy (int stamina, int food) {
     energy = energy + stamina;
     stomach = stomach + food;
  }
]]
```

Within the code fragment the user can do anything that can be done from within a typical C++/ECO program. However, it would be wise to limit individual actions to perform only simple modifications to the attributes, or invocations of inherited methods.

The state of the Entity must be contained in a single enclosing state, typically an XOR or AND state. Within a state there can be several sub-states. The current syntax supports XOR states, AND states and elementary states. The hierarchical nature of statecharts is conveniently represented by the nesting of state statements. Consider the following example (see Figure 2.38).

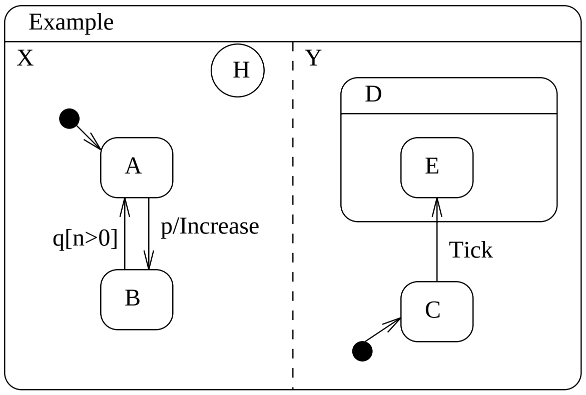


Figure 2.38: Example Statechart for encoding.

```
xorstate ‘‘Example’’ (left=0,right=300,top=0,bottom=200)
{
  andstate ‘‘X’’ (left=0,right=150,top=10,bottom=190)
  {
    shallowhistory;
    state ‘‘A’’ (left=60,right=80,top=10,bottom=30);
    state ‘‘B’’ (left=60,right=80,top=90,bottom=110);
    trans ‘‘A’’ to ‘‘B’’ (curve=1) on p do Increase;
    trans ‘‘B’’ to ‘‘A’’ (curve=1) on q when (num>0);
    default ‘‘A’’ (x=55,y=15);
  }
  andstate ‘‘Y’’ (left=150,right=300,top=10,bottom=190)
  {
    state ‘‘C’’ (left=30,right=50,top=80,bottom=100);
    xorstate ‘‘D’’ (left=....)
    {
      state ‘‘E’’ (left=...);
    }
    trans ‘‘C’’ to ‘‘D’’.’’E’’ (curve=1) on Tick;
    default ‘‘C’’ (x=...);
  }
}
```

The bracketed expressions after the state names are properties of the state, and are used to store the graphical information about the state. This information would be used by the Entitor to recreate the same looking statechart. Similar properties are included for the transitions. In this example `curve` dictates what type of curve should be used to draw the transition line. (`curve=1` signifies a straight line).

2.5.4 Grammar

The following represents a basic grammar for the Entity File Format. The syntax used defines multiple productions from the one non-terminal symbol. If the modifier 'opt' is placed after a non-terminal it means that it is optional. Definitions for elementary non-terminals are not given.

```
<DECLARS>
  -> <DECLAR>
  -> <DECLAR> <DECLARS>
  ->

<DECLAR>
  ->  event <IDENT> <PARAMDECLS>opt ;
  ->  attribute <IDENT> : <TYPE> ;
  ->  action <IDENT> <PARAMDECLS>opt <FRAGMENT>
  ->  <STATEDECL>

<STATEDECL>
  ->  xorstate <STNAME> <PROPTYS>opt { <SUBS> }
  ->  andstate <STNAME> <PROPTYS>opt { <SUBS> }
  ->  state <STNAME> <PROPTYS>opt ;

<SUBS>
  ->  <SUB>
  ->  <SUBS> <SUB>

<SUB>
  ->  <STATEDECL>
  ->  deephistory;
  ->  shallowhistory;
  ->  default <STNAME> <PROPTYS>opt ;
  ->  trans <DEEPSTNAME> to <DEEPSTNAME> <PROPTYS>opt <TRANSDECL> ;

<TRANSDECL>
  ->  <TREVENT>opt <TRCONST>opt <TRACTION>opt

<TREVENT>
  ->  on <IDENT>

<TRCONST>
  ->  when <FRAGMENT>

<TRACTION>
  ->  do <FRAGMENT>

<PASSPARAMS>
  ->  ( <PASSPLIST> )

<PASSPLIST>
```

```
  ->  <IDENT>
  ->  <VALUE>
  ->  <IDENT> , <PASSPLIST>
  ->  <VALUE> , <PASSPLIST>

<PARAMDECLS>
  ->  ( <PARAMDLIST> )

<PARAMDLIST>
  ->  <IDENT> : <TYPE>
  ->  <IDENT> : <TYPE> , <PARAMLIST>

<PROPTYS>
  ->  ( <PROPTYLIST> )

<PROPTYLIST>
  ->  <IDENT> = <VALUE>
  ->  <IDENT> = <VALUE> , <PROPTYLIST>

<FRAGMENT>
  ->  [[ <FRAGMENTCODE> ]]

<EXPRESSION>
  ->  [[ <FRAGMENTCODE> ]]

<DEEPSTNAME>
  ->  <STNAME>
  ->  <STNAME> . <DEEPSTNAME>

<STNAME>
  ->  ‘‘ <TEXT> ’’
```

2.5.5 Example

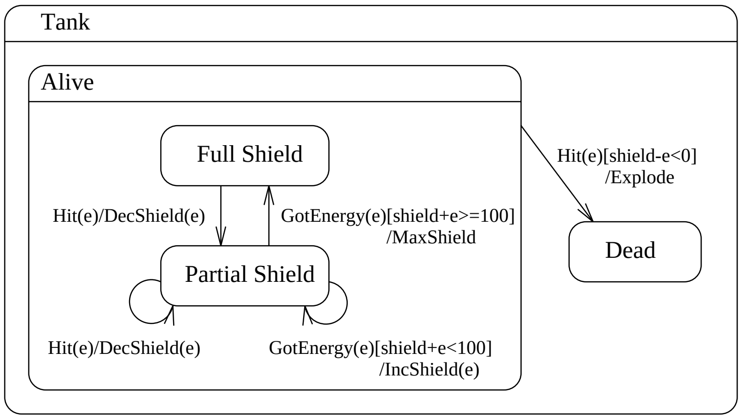
The following is a short example of a typical Entity Definition File. See Figure 2.39 for graphical representation.

```
event Hit (e : int);
event GotEnergy (e : int);

attribute [[int shield;]]

action [[
  MaxShield ()
  {
    shield = 100;
  }
]]

action [[
  IncShield (int x)
  {
```



Actions	
DecShield (e : int)	shield = shield - e;
IncShield (e : int)	shield = shield + e;
MaxShield	shield = 100;
Explode	(Change graphics)

Attributes
shield : int

Figure 2.39: Example of a simple Tank statechart.

```
    shield = shield + x;
  }
]]

action [[
  DecShield (int x)
  {
    shield = shield - x;
  }
]]

action [[
  Explode
  {
    //perform some graphical changes
  }
]]

xorstate ‘‘Tank’’ (left=0,right=300,top=0,bottom=200)
{
  xorstate ‘‘Alive’’ (left=...)
  {
    state ‘‘Full Shield’’ (left=...);
    state ‘‘Partial Shield’’ (left=...);
    trans ‘‘Full Shield’’ to ‘‘Partial Shield’’ (curve=1)
      on Hit do [[DecShield(e);]]
    trans ‘‘Partial Shield’’ to ‘‘Full Shield’’ (curve=1)
```

```
      on GotEnergy when [[(shield+e>=100)]] do [[MaxShield();]]
    trans ``Partial Shield'' to ``Partial Shield'' (curve=2)
      on Hit do [[DecShield(e);]]
    trans ``Partial Shield'' to ``Partial Shield'' (curve=2)
      on GotEnergy when [[(shield+e<100)]] do [[IncShield(e);]]
    default ``Full Shield'';
  }
  state ``Dead'' (left...);
  trans ``Alive'' to ``Dead'' (curve=1)
    on Hit when [[(shield-e<0)]] do [[Explode ();]]
}
```

2.6 Entity Editor Code Generator

This section considers how Entity classes should be represented in C++/ECO. The Entity Editor should be able to output source code in C++/ECO which can be compiled, linked and executed within the VOID execution environment. This source code is a C++/ECO representation of the statechart, actions and attributes of the Entity

The general problem is two-fold. Firstly, code which executes as a state machine modelling the Entity statechart must be generated. Secondly, any code fragments (actions, constraints etc) must be translated into the target source language.

While it would be ideal to make the Entity Editor language independent, the immediate solution is to produce code only for C++/ECO. If the user is required to enter all code fragments in the chosen target language, then no code translation need occur. However, the problem of generating the state machine still remains.

2.6.1 Starting Point

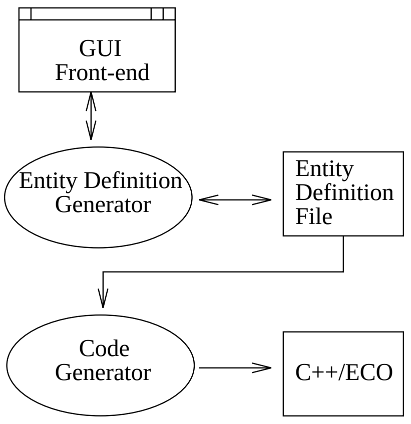


Figure 2.40: General structure of the Entity Editor.

From Figure 2.40 it can be seen that the Code Generator is considered to be a separate program. The fundamental point is that the Code Generator takes as input the Entity Definition File, and outputs a representation of the Entity in the target language. The other alternative to code generation would be to allow the generator have access to the internal structures of the Entity Editor, and produce the target language code from there. This would probably mean making the code generator part of the Entity Editor program.

Based on the philosophy that a programs internal data structures should be designed around the requirements of that program, it would appear that two separate data representations are required. One for the graphical manipulation of the statechart in the Entity Editor; and one for translation purposes in the Code Generator. While it may be possible to resolve these two structures into one, keeping them separate simplifies their design. In addition it may simplify the design and implementation of the two programs; the Entity Editor and the Code Generator.

Given that we have a standard Entity File Format, we need to build a single interchange layer to convert from the file format to the Code Generator's internal representation. This is the principle cost involved in having a separate Code Generator. Considering the clean division of problem provided by this design approach, it is an acceptable cost. So the decision is to have the Code Generator as a separate program from the main of the Entity Editor.

2.6.2 No Reverse Engineering

One noticeable omission from the design is that it is not possible to convert C++/ECO code to the Entity Definition File format. The general problem of converting an arbitrary C++/ECO program to statechart form is simply too complex. Even the simplified problem of taking code initially produced by the code generator, but subsequently altered slightly, and mapping it back to a statechart is very complex.

If small changes need to be made to the code produced by the Entity Editor, they should be made at the level of the Entity Editor instead. This is quite easy if the change is to an action. If the change is to the state machine then the correct approach would be to identify the changes at a statechart level, and not by making almost arbitrary changes to relatively complex code generated automatically.

2.6.3 Basic Statechart to Code Mapping

The problem to solve is the automatic generation of a state machine that simulates the Entity's statechart. This section outline a C++/ECO specific solution, which deals with simple statecharts. Complexities, such as orthogonality, are dealt with in more detail later.

2.6.3.1 Direct Mappings

Assumptions made about the target language (C++/ECO) mean that many concepts present at the Entity level can be mapped directly to the target language level.

- An Entity class maps to a single C++/ECO class.
- An Attribute of an Entity classes maps to a single data member of a C++/ECO class.
- The Events exchanged between Entities are mapped directly to the events supported by C++/ECO.
- The ability of an Entity to raise an event is directly mapped to the raising of an event in C++/ECO.
- The FIFO queueing of events is provided by C++/ECO.
- Named Actions are mapped to methods of the C++/ECO class.
- Direct Actions are mapped to code fragments of C++/ECO.
- The constraints on transitions in the Entity statechart are mapped directly to conditional expressions of C++/ECO.

2.6.3.2 Event Handling

The processing of event notifications at the Entity level is quite different than at the C++/ECO level. In the former case, an event potentially triggers constraint evaluations and state transitions, each possibly executing an action. In the latter, an event triggers the evaluation of a number of pre-conditions, each of which may trigger a method - no state is maintained.

To achieve a mapping between the two, the C++/ECO methods must perform the Entity constraint evaluation, update the state variables and execute the appropriate actions.

Event subscription and unsubscription are considered heavy-weight operations, so they cannot be done on every state transition. So to avoid the overhead of unsubscribing and resubscribing to events as the state of an Entity changes, an Entity simply subscribes to all the events it will every require when it is created, and unsubscribes from them when it is destroyed. This means that while an Entity may be in a particular state waiting for one particular event, the underlying C++/ECO object may remain subscribed to many more events. [1]

The facilities provided by C++/ECO allow an event to invoke a number of preconditions, each of which can invoke a fixed method. The precondition facility is used as a filter to determine if the event that arrived is currently accepted by the state machine. If it's in a state that has a transition that depends on the arrival of that event, then the precondition succeeds and triggers the method.

The method in question is written specifically to handle that particular event. It is referred to as an **event-handler** method. There is one such method for each event of interest to the Entity. Conceptually, it is responsible for determining what state the entity is in, and as a result, what needs to be done. The apparent concurrency provided by the AND states is simulated here. If the **event-handler** finds that the state machine is in an AND state, then it must cater for the two active states.

The **event-handler** method actually delegates the work to one or more **depart-on** methods. These are methods which responsible for departing from a particular state on the arrival of a particular event. For each set of transitions in a statechart that leave the same state and are triggered by the same event there is a unique **depart-on** method. When these methods are executed, they assume the state machine is in a particular state and that a certain event has occurred. They are responsible for determining which of the transitions is to be taken, executing the chosen transitions action, and putting the state machine in a new state.

In most cases the **depart-on** method will only have to deal with one transition. However, if a state has many transitions leaving it by the same event, then the **depart-on** method will have to evaluate the constraints of each transition until it finds one that can be taken. Note that the first transition evaluated with a valid constraint will be taken. (This is in keeping with comments made about non-determinism in statecharts.)

2.6.3.3 State Maintenance

As mentioned above, *conceptually*, the **event-handler** methods are responsible for determining what state the state machine is currently in. However, as the last transition will have placed the state machine in some known state, it would be wasteful for the **event-handler** to perform any kind of `switch` operation. Instead, when a transition places the state machine in some new state, what actually occurs is that changes are made to a table of **depart-on** method references.

At any given time, this table determines the current state, as it defines what **depart-on** methods must be invoked by each of the **event-handlers**. The table is actually a number of lists. For each **event-handler** there is a list of **depart-on** method references that must be invoked when the **event-handler** runs.

When an event arrives, it first triggers a particular precondition. This examines the list of **depart-on** references for that event, and only triggers the associated **event-handler** if it is not

[1] User level support may be provided by the Entity Editor to allow the user to suggest to the Code Generator that dynamic subscription and unsubscription would be more optimal in particular situations.

empty. If it is empty, then the state machine is simply not in a state that requires that event, and it is discarded. (This is consistent with the view that a statechart only accepts sequences of events that match it's 'event language'.)

When invoked, the **event-handler** invokes each of methods specified in the appropriate**depart-on** method list. Precautions are taken to ensure that the first **depart-on** method does not over-write the list before it is fully used. The list of **depart-on** methods is sorted by their depth order. Those entries departing from outermost states are dealt with first. This is to ensure that apparent non-determinism is solved by only taking the outermost transition. If the outermost is not taken because it's constraint fails, then the inner ones have a chance to execute.

2.6.3.4 Scope in Actions and Constraints

The fragments of code that the user enters as the Actions or Constraints is used verbatim in the mapping from statecharts to C++/ECO. While the user may potentially enter anything at all, some consideration should be given to what is sensible for them to access. [2]

For a constraint the user should enter a typical C++/ECO expression which will evaluate to either true (non-zero) or false (zero). The variables that should be considered in-scope are the event parameters and the attributes of the Entity. Access to the state of the Entity is provided through special functions.

Direct Actions are simply a number of C++/ECO statements that the user associates with a particular transition. They have no identifying name, so cannot be accessed by other transitions. As with constraints, the variables that should be considered in scope are the Attributes and event parameters. Queries about the current state can be made through special functions.

Named actions are ordinary C++/ECO methods. They can have local variables, and can access the attributes of the Entity as well as the values of their own parameters. However, in contrast to constraints and direct actions they cannot access the parameters of the event that ultimately triggered their invocation. Note that in practise every transition that performs some action has a direct Action associated with it. Transitions that appear to invoke a named Action do so via a single statement direct action which invokes the named Action.

2.6.4 Simple Example

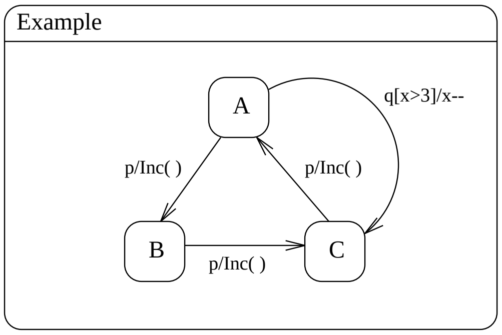


Figure 2.41: A Simple Statechart.

To demonstrate the general format of the code produced by applying the mechanisms described above, consider the following example. A typical graphical representation of the Entity class is given in figure 2.41. The statechart has three elementary states, each of which responds to event `p` by invoking the named Action `Inc` and moving along the cycle. State `A` also responds to event `q`

[2] Obviously the potential for user error is significant, and in subsequent versions of the tool, code-creating facilities may need to be provided to help the user write correct code.

when the constraint [x>3] is true, invoking the direct Action x--. The Entity has one attribute, x and one named Action Inc.

2.6.4.1 Depart-on Lists

Many of the details are hidden in the depList class. This is primarily for clarity. A depList class contains a list of pointers to methods. Each of these methods is a **depart-on** method in the Example class. The declaration of the depList class might be as follows:

```
class depList {
    // The depart-on method pointers, classified by depth
    void *methodPointers[MAXDEPTH][MAXENTRIES];

    // Temporary storage area for Adds while executing.
    void *tempPointers[MAXTEMPS];
    int tempDepths[MAXTEMPS];

    void Clear () {
       // Clear all methodPointers
       // totalEntries = 0
    }
    int TotalEntries ()
    {
        return (totalEntries);
    }
    void Execute (event e, void *pointerSelf)
    {
       // Invoke each method pointed to by methodPointers,
       // starting from the outermost depth and working in.
       // Add the tempPointers to the methodPointers.
    }
    void Add (void *pointerToMethod, int depth)
    {
       // If this depList is currently executing Then
       //    Add this pointer to the tempPointers
       // Else Add this pointer at the specified depth
       // totalEntries ++
    }
    void Remove (void *pointerToMethod, int depth)
    {
       // Remove pointer at a given depth
       // totalEntries --
    }
}
```

The use of this class may be changed in the actual implementation. For the purposes of design, it provides a useful abstraction, as it removes many of the complexities of dealing with pointers to methods. The issues related to the depth of a transition are dealt with later.

2.6.4.2 C++/ECO Code

While the syntax for the Entity class attempts to remain faithful to that proposed in [56], the purpose of this example is to demonstrate the overall mechanism, rather than the specific syntax.

```
class Example {

    int x;          // Attributes

    Inc () { x++ }  // Actions

    depList pDepList;  // Depart-on lists
    depList qDepList;

    inevents pEevent, qEvent;  // Declare events.

    // Preconditions
    constraint pPrecond {
        if (pDepList.totalEntries() == 0) discard;
        else process-passive;
    }
    constraint qPrecond {
        if (pDepList.Empty ()) discard;
        else process-passive;
    }

    // Event handlers
    pHandler (event e) { pDepList.Execute (e, self); }
    qHandler (event e) { qDepList.Execute (e, self); }

    // Register for events
    pHandler handles (pEvent, NULL, pPrecond, NULL);
    qHandler handles (qEvent, NULL, qPrecond, NULL);

    // Constructor
    Example () {
        pDepList.Clear ();
        qDepList.Clear ();
        // Setup initial state
        pDepList.Add (&dep_A_On_p, 1);
        qDepList.Add (&dep_A_on_q, 1);
    }

    // Methods for Departing from <state> on event <event>
    dep_A_on_p (event e) {
        Inc ();  // The action
        qDepList.Remove (&dep_A_on_p, 1);
        pDepList.Remove (&dep_A_on_q, 1);
        pDepList.Add (&dep_B_on_p, 1);
        return (1);
    }
    dep_B_on_p (event e) {
        Inc (); // The action
        pDepList.Remove (&dep_B_on_p, 1);
        pDepList.Add (&dep_C_on_p, 1);
        return (1);
    }
    dep_C_on_p (event e) {
        Inc (); // The action
        pDepList.Remove (&dep_C_on_p, 1);
        pDepList.Add (&dep_A_on_p, 1);
        qDepList.Add (&dep_A_on_q, 1);
        return (1);
    }
    dep_A_on_q (event e) {
        if (x > 3) { // constraint
            x--; // The action
            pDepList.Remove (&dep_A_on_q, 1);
            qDepList.Remove (&dep_A_on_p, 1);
            pDepList.Add (&dep_C_on_p,1);
            return (1);
        }
        return (0);
    }
}
```

Note that each **depart-on** method returns one or zero, depending on whether the transition was actually taken or not. This is so that `depList.Execute()` can determine whether transitions that are deeper should be given a change to execute. [3]

2.6.5 Depth

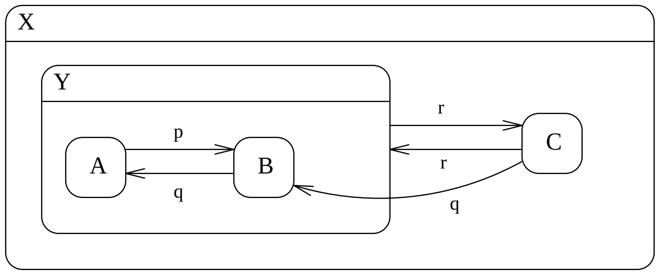


Figure 2.42: Statechart illustrating depth.

Consider the statechart in figure 2.42. Transitions which originate from a compound state (such as the transition from Y to Z) introduce the complication of recursively *exiting* from that state. Examine the **depart-on** methods in the last example. A general form for such a method might be:

```
If (constraint is true) Then
    Perform some action.
    Exit from the source state of the transition
     (ie Remove depart-on methods of source state.)
    Enter the destination state of the transition.
     (ie Add depart-on methods of destination state.)
```

[3]This means there is actually a dependency between the action code and the state machine code. The state machine code has, in effect, read access requirements on the attributes. If the actions are considered as sequential code and the state machine as synchronisation code, then it is impossible to separate the sequential and synchronisation code. In such a situation it is not desirable to have internal concurrency within an object, as deadlock may occur (readers/writers problem). See [44].

```
    Return (1)
EndIf
Return (0)
```

In the case of an elementary state, the *exiting* is achieved by simply removing the **depart-on** methods of the current state from the various DepLists. However, in Figure 2.42 the transition from Y to Z must exit from an XOR state. The `dep_Y_on_r` method must actually call a special method `exit_Y`. This identifies which sub-state is active (A or B) and removes the appropriate **depart-on** methods. As the sub-states could be compound states (XOR or AND) the **exit** methods may need to call other **exit** methods.

For each AND and XOR state there is a single **exit** method, which is responsible for removing the **depart-on** methods from the DepLists of itself, and all it's sub-states. To achieve this, special **state-variables** must be maintained. In the example, there would be a `Ystatevar` variable which could hold the value `A_STATE` or `B_STATE`. Before an **exit** function terminates, it either resets these variables to default values, or leaves them as they are. This provides the defaulting and history abilities of the statechart. [4]

Similarly, for each compound state there is a single **enter** function, with responsibility for recursively adding the appropriate **depart-on** methods to the DepLists. This is done on the basis of the current values of the **state-variables**. In the case of the transition from Z to Y, the **Depart-on** method simply calls `enter_Y`. In the case of the transition from Z to B, the **Depart-on** method must first set the value of Y's **state-variable** to B, and then call `enter_Y`.

With reference again to Figure 2.42, the enclosing state, X, is considered to be at a depth of 0. The sub-states of this state (Y and Z) are at depth 1. Similarly, the sub-states of Y are at depth 2, and so on. The **depart-on** methods would be as follows.

```
dep_Y_on_r (event e)
{
    exit_Y ();  // Remove all X depart-ons
    Xstatevar = Z_STATE;
    rDepList.Add (&dep_Z_on_r, 1);
    rDepList.Add (&dep_Z_on_q, 1);
    return (1);
}
dep_Z_on_r (event e)
{
    rDepList.Remove (&dep_Z_on_r, 1);
    rDepList.Remove (&dep_Z_on_q, 1);
    XStatevar = Y_STATE;
    enter_Y ();
    return (1);
}
dep_Z_on_q (event e)
{
    rDepList.Remove (&dep_Z_on_r, 1);
    rDepList.Remove (&dep_Z_on_q, 1);
    XStatevar = Y_STATE;
    YStatevar = B_STATE;
    enter_Y ();
    return (1);
}
```

[4] The difference between shallow and deep histories does not arise at this level. Each XOR or AND state either has history, or uses defaults. Deep history simply means that all sub-states have histories.

```
dep_A_on_p (event e)
{
    pDepList.Remove (&dep_A_on_p, 2); // state A is at depth 2
    Ystatevar = B_STATE;
    pDepList.Add (&dep_B_on_p, 2);
    return (1);
}
dep_B_on_p (event e)
{
    pDepList.Remove (&dep_B_on_p, 2);
    Ystatevar = A_STATE;
    pDepList.Add (&dep_A_on_p, 2);
    return (1);
}

exit_Y ()
{
    switch (Ystatevar) {
    case A_STATE :
        pDepList.Remove (&dep_A_on_q, 2);
        break;
    case B_STATE :
        pDepList.Remove (&dep_B_on_p, 2);
        break;
    }
    Ystatevar = A_STATE; // reset to default
}
enter_Y ()
{
    switch (Ystatevar) {
    case A_STATE :
        pDepList.Add (&dep_A_on_q, 2);
        break;
    case B_STATE :
        pDepList.Add (&dep_B_on_p, 2);
        break;
    }
}
```

Any transition which effectively crosses the bounds of an XOR or AND state must invoke the appropriate **enter** or **exit** method. Elementary states do not have these function, so the **depart-on** methods must perform the Adds and Removes directly. The **enter** and **exit** methods of a state do not affect the **state-variable** of their containing state. In the example, the `exit_Y` method does not affect the `Xstatevar`. The **depart-on** method must update it.

The **exit** and **enter** methods add some overhead to the transition mechanism. However, as the frequency of transitions between complex states is almost certainly going to be lower than between elementary states, this is acceptable. [5]

2.6.6 Orthogonality

[5] As is so common in implementation, the objective is to optimise the most frequent cases.

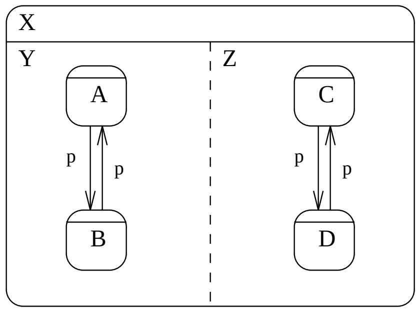


Figure 2.43: Example of an AND State.

Consider the statechart in Figure 2.43. If it were in states A and C, there would be two entries in the DepList for event p, at depth 1: `dep_A_on_p` and `dep_C_on_p`. When the p event is detected, the `depList.Execute` method executes both of the methods listed at depth 1. This execution is done in a serial fashion. Orthogonal states do not mean concurrency, they only imply independence.

2.6.7 Unstable states

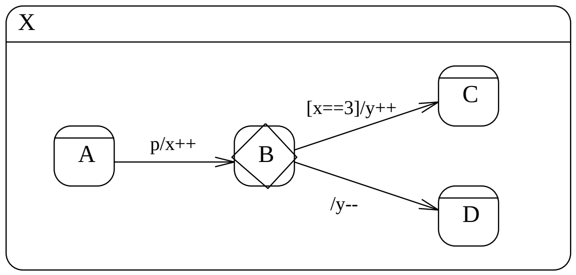


Figure 2.44: Example of an unstable state.

Unstable states are not implemented as true states. They are considered links in a chain of actions that must be executed in response to a single event. The chain must always end at a stable state. For this reason, every unstable state must have an unbound transition leaving it. This is taken if all other transitions are inactive.

The code produced for a chain must determine what actions are to be executed and what final state to enter. Consider the following **depart-on** method which implements the statechart in Figure 2.44:

```
dep_A_on_p (event e)
{
    x ++;  // Action
    exit_A ();
    if (x == 3) {
        y ++
        Xstatevar = C_STATE;
        enter_C ();
    } else {
        y --;
        Xstatevar = D_STATE;
        enter_D ();
    }
    return (1);
}
```

2.6.8 Non-determinism

Pure non-determinism, where more than one transition is active from a state at one time, is removed by simply ignoring all but one of the transitions at code generation. The resulting code represents a statechart with only one transition, which is deterministic.

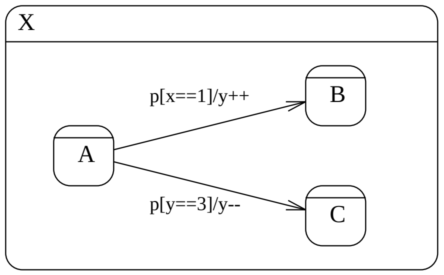


Figure 2.45: Example of Potential Non-determinism.

Potential non-determinism, where many transitions from a state may be active at the same time depending on their constraints, is dealt with by the **depart-on** method. The first active transition found is taken, and all the others are ignored. Consider the following example, which implements the **depart-on** method for Figure 2.45.

```
dep_A_on_p (event e)
{
     if (x == 1) {
         y ++;  // Action
         exit_A ();
         Xstatevar = C_STATE;
         enter_A ();
         return (1);
     } else if (y == 3) {
         y --;  // Action
         exit_A ();
         Xstatevar = B_STATE;
         enter_A ();
         return (1);
     }
     return (0);
}
```

Apparent non-determinism is dealt with by the `DepList.Execute()` method. The non-determinism is removed by applying outermost priority. Consider the statechart in Figure 2.46. If in states A and C, pDepList contains references to methods:

- At depth 1: `dep_Y_on_p`
- At depth 2: `dep_C_on_p` and `dep_Z_on_p`
- At depth 3: `dep_A_on_p`

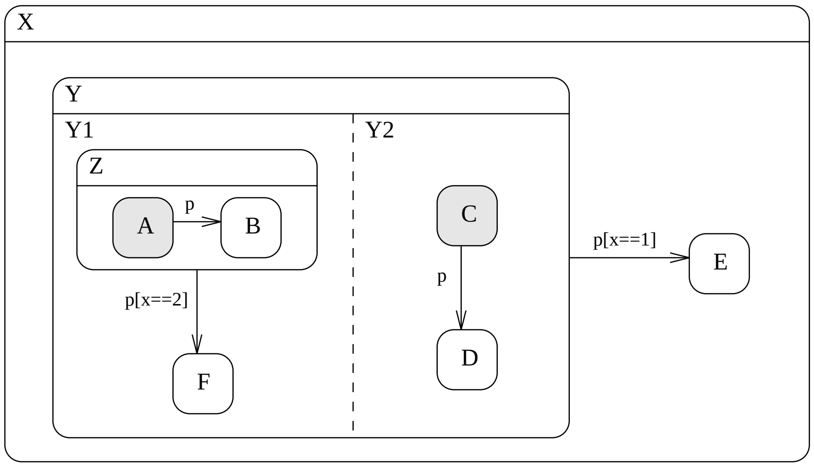


Figure 2.46: Example of Apparent Non-determinism.

Consider the case where `x=1`. When `pDepList.Execute()` is called the outermost **depart-on** method is evaluated first, `dep_Y_on_p`. As the constraint is satisfied, the transition will be taken. However, one of the things that `dep_Y_on_p` does is to call `exit_Y`, which removes all the other **depart-on** methods from the `pDepList`. This means that no further transitions will be evaluted, and the desired affect is achieved.

However, if `x=2` then the outermost transition will fail (return zero), so `pDepList.Execute()` must execute both `dep_C_on_p` and `dep_Z_on_p`. The execution of one will not affect the execution of the other, as they are orthogonal. As `dep_Z_on_p` succeeds, `exit_Z` will remove `dep_A_on_p`, so it will never be processed.

The final case is if `x=3`. The `dep_Z_on_p` method will fail, so it will not remove `dep_A_on_p`, which is then executed. The transition from C to D will be taken regardless of whether `x=2` or `x=3`.

While it is desirable to have the `pDepList.Remove()` calls register within the `pDepList` immediately, it is not desirable to have the `pDepList.Add()` calls register, as it could mean that the `Execute` may perform more calls that is required. So the first thing the `Execute()` method must do is ensure that `Add()` calls delay the registration of new **depart-on** methods until the `Execute()` cycle is complete. So the `Add()` method simply notes the details, and leaves the work of adding them to `Execute()` when it is complete.

2.6.9 Summary

The generation of C++/ECO code that effectively models an Entity definition is a complex process. This section has presented an approach that may be taken to the mapping from the higher level concept of an Entity (with statecharts, actions and events) down to the lower level concept of a C++/ECO class (with events, pre-conditions and methods).

Chapter 3

ECOlib: Support For Events, Constraints, and Objects

3.1 Introduction

This chapter describes the interface to the ECO library (ECOlib) and contains some details about its implementation. The library provides low-level runtime support for inter-object communication based on events and constraints, and as such it is a part of the Moonlight VOID shell.

This introductory section briefly and informally describes the ECO programming model. It also gives the assumptions about the underlying system and assumptions about the ECOlib user. The following section specifies the ECOlib primitives and predefined events. The ECOlib is being implemented, and in several places in this chapter we list the possible implementations of some part of the interface. The last section summarises the preceding text and mentions some future work.

3.1.1 Programming with events, constraints, and objects

In the ECO model objects communicate among themselves using events and constraints. An **event** represents something that can happen, and it has name and zero or more parameters. The name of an event allows the objects to refer to a specific event among all the events. The parameters of an event have type (e.g., an integer or a character string). For the specific occurrence of an event the parameters are instantiated with values. These values, together with the event name, describe to the objects what happened, i.e., describe the specific occurrence of an event[1].

An **object** encapsulates some data and some processing. An object can tell other objects about something that happened, and it can react if it is told by other objects that something happened. The former is accomplished by *announcing* an event, and the latter by binding a method of the object to the required event. This binding can be dynamic, i.e., it is allowed to unbind a method from an event. The same method can be bound to several events, and the same event can have several methods (of the same or of different objects) bound to it. A binding can be established only if the signatures of the event and of the method match (if they have the same number of parameters, and the types of the corresponding parameters are the same).

Constraints enable more flexible event-method bindings and more flexible processing of event notifications. An object may conditionally be interested in some event: it is interested only if the specific event parameter has a specific value or any value from a range of values when the event is announced. This can be expressed using the so called *Notify constraints*. In addition to this,

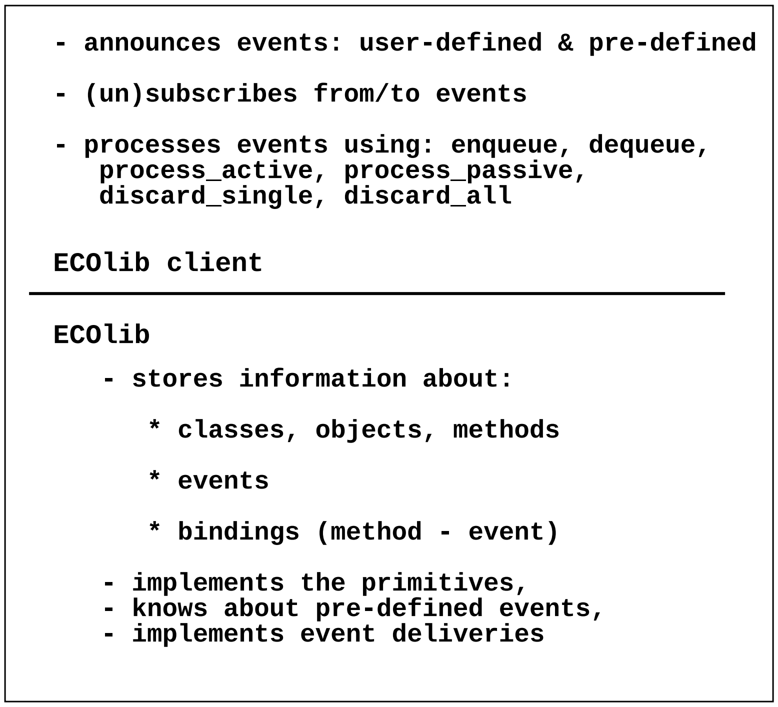
[1]In the following text we use "event" for both an event and an event occurrence. The context will indicate the correct interpretation.

an object may decide, based on the object's local state when it is told about an event, that the processing of the event should be postponed or even cancelled.

If the local state is such that the processing should go ahead, it may be the case that multiple flows of control are allowed within the object. In general the object may require that there should be a maximum n concurrent flows of control within the object, where $n = 1, \ldots, N$ (where N is object dependent). An example of multiple flows of control within an object is when the object uses a *multiple-readers single-writer* policy, and the object knows which of its methods are "readers" and which of them are "writers".

All these options (postponing and cancelling processing of an event, controlling the level of concurrency within an object) are available from the so called *Pre constraints*. Both *Pre* and *Post constraints* are associated with an event-method binding. The two kinds of constraints act as a method wrapper. Constraints have no parameters and return a result which is *true* or *false* (i.e., a constraint is either satisfied or not satisfied). Constraints which depend only on the constraint internal data (and do not depend on any global data or object local data) can be reused by different objects.

The ECOlib library implements a low-level runtime support for the events constraints and objects. It maintains information about classes, objects, events and their occurrences, and information about various bindings. It knows about a number of *predefined events*. The library itself uses events. More about the ECO model, and a programming language syntax for this model, can be found in [53], reproduced in appendix C. The separation of functionality between the ECOlib and its client is shown in figure 3.1.



```
- announces events: user-defined & pre-defined

- (un)subscribes from/to events

- processes events using: enqueue, dequeue,
   process_active, process_passive,
   discard_single, discard_all

ECOlib client
______________________________________________

ECOlib
   - stores information about:

      * classes, objects, methods

      * events

      * bindings (method - event)

   - implements the primitives,
   - knows about pre-defined events,
   - implements event deliveries
```

Figure 3.1: Separation of functionality between the ECOlib and ECOlib client code.

3.1.2 Assumptions about the ECOlib environment

First, the assumptions about the underlying system. It is assumed that there is support for lightweight threads. The ECOlib requirements are basically to be able to start a thread and to ensure mutual exclusion of threads. It is also assumed that there is preemptive scheduling of threads, and that this is required by applications.

Next, assumptions about ECOlib's users. The intended client of ECOlib (i.e., the user of the interface described in this chapter), is the code which will be generated by a language processor or by one of the Moonlight tools. The following is assumed:

- When an object is created, the client will allocate the space for object data and assign a unique identifier to the object. The ECOlib will be informed about the creation of each object, if this object is to use events and constraints. This is done using the *announce* primitive, and the name of the event announced is *object_created* (one of the predefined events).

- In a class-based language a class can play several roles. It is assumed here that a class allows method sharing and interface sharing for the objects or instances of a class. When a class is created the ECOlib is informed about this, and is passed some information about that class (the client announces the *class_created* predefined event).

- When a class, or an object, is deleted the ECOLib is informed about this (the client announces the appropriate predefined event).

- Binding between methods of an object and events is dynamic and based on the use of subscribe and unsubscribe. The user of ECOlib is responsible for creating these bindings, and later for modifying them. Specifically, there is predefined event called *error*, which is announced internally by the ECOlib when some error conditions are detected. This event is delivered only to those objects which established a binding for the event.

- When an event is announced and the event has parameters then it is up to the user of ECOlib to marshal the parameters into a single block of memory. A pointer to this block is passed to ECOlib when the event is announced. When an event is being delivered to a method, a pointer to a block of memory which contains the event parameters is passed to the method. It is up to the method to unmarshal these parameters and invoke the application level code which implements the method.

Different programming language constructs (from the same language or from different languages) may be translated into the code which will use the ECOlib interface. There is an obvious mapping from the language constructs described in [53] and the primitives and predefined events described in this chapter.

3.2 The ECOlib interface

This section specifies the ECOlib entry points or primitives, and a collection of the predefined events.

3.2.1 The ECOLib internals

This subsection describes some internal ECOlib data (the *event notification packet*, *current object*, *current method*, and *current event*). They are given only in order to simplify the interface desciption which follows. The implementation of the ECOlib is not constrained in any way by the given specification of its internal data.

The ECOlib maintains information about the current object, current method, and current event. This internal information is used by some of the primitives. The event notification packet (ENP) is also internal to the ECOlib, i.e., it is not visible at the ECOlib interface. Whenever an event is announced the ECOlib creates an event notification packet which is outlined below.

```
struct enp {             /* event notification packet */

        char* name_enp;   /* name */
        enpbody data_enp; /* parameter values */
}
```

An ENP can be shared by a number of destinations, i.e., it can belong to a number of *paths* (a path links ENPs which belong to a single destination). Thus, the ENPs form a graph structure. An ENP has, for each of the paths to which it belongs to, information about the priority of the ENP relative to other ENPs on the same path. These priorities, if they are used, order the notifications before they are delivered to their destination. The ENPs on a single path are called the *ready* ENPs. Each binding between a method and an event can have its list of *waiting* ENPs — those which are managed by the object itself using the *enqueue* and *dequeue* primitives (these primitives are described below).

3.2.2 The primitives of the interface

A list of the primitives is given below. More information about each of them can be found in the following text.

- **announce** *event_name(param_value, param_value, ...) priority*
- **subscribe** *method_name(event_name, notify_name, pre_name, post_name)*
- **unsubscribe** *method_name event_name*
- **process_passive**
- **process_active** *priority*
- **enqueue**
- **dequeue** *method_name, event_name*
- **discard_single**
- **discard_all**

announce is the main primitive of this interface, it can be called from methods and from Pre and Post constraints. The implementation of some of the other primitives use event announcement, specifically *subscribe* and *unsubscribe* are syntactic sugar — they are implemented as announcements of the corresponding internal events (this is done in order to simplify concurrent handling of "ordinary", i.e., application-specific, events and handling of *subscribe* and *unsubscribe*). The remainder of the primitives from the list are expected to be called from Pre and from Post constraints. The primitives which can be called from Pre constraints are: *process_passive*, *process_active*, *enqueue*, *dequeue*, *discard_single*, and *discard_all*. The primitives which can be called from Post constraints are: *enqueue*, *dequeue*, *discard_single*, and *discard_all* (note that there is an implicit *discard_single* after a Post constraint). The users affect the order in which the events happen (i.e., the order in which the events are announced and handled) by using priorities. More about priorities is given in 3.2.2.1. A specification of the above primitives in the form of a C++ class[2] is given below.

[2]The use of C++ for the specification of this interface does not indicate that the C++ object model lies under the Moonlight object model.

```
class ECOlib {

  public:
        announce(event_name, par_values, priority);

        subscribe(method_name, event_name, notify_name, pre_name, post_name);

        unsubscribe(method_name, event_name);

        process_passive();

        process_active(priority);

        enqueue();

        dequeue(method_name, event_name);

        discard_single();

        discard_all();
}
```

The following text describes the above primitives.

announce primitive

This primitive is used to announce the occurrence of the named event. The input to this primitive is: the name of the event which is being announced, the values of the parameters for this event occurrence, and (optionally) the priority of this event occurrence.

The named event must be known to ECOlib (i.e., the predefined event called *create_event* with this event as parameter was previously announced). Before *announce* is called, the values of the parameters which are passed to ECOlib have to be marshalled in a block of memory of the size specific for this event. The priority indicates the required ordering of this event occurrence with respect to occurrences of other events.

The ECOlib stores the input information into an ENP for further processing: for finding the bindings for this event, for evaluating the Notify constraints, and for delivering the notification to the destinations. However, this processing is done internally by the ECOlib. After *announce* the announcer object continues with its processing, i.e., *announce* is an asynchronous operation: it transfers information, it does not transfer control.

subscribe primitive

This primitive is used to request a binding between the named method and the named event. The method has to be a method of the current object, and its signature has to match the event signature. The event has to be one of the events which the class of the current object can handle (one of the events declared as such when the class creation was announced). The named constraints are optional, and if they are given have to be local to the object class.

This primitive creates a binding between the method and event. The same primitive can also be used to change a binding (give different constraints to an existing binding). It is implemented as an announcement of the *subscribe_internal* event, which means that the primitive is asynchronous — the announcer does not wait for the binding to be fully established.

unsubscribe primitive

This primitive is used to break the binding between the named method of the current object and the named event. It is implemented as an announcement of the *unsubscribe_internal* event. There are several options for an implementation of this primitive: (1) all the notifications which may be enqueued on the given binding are discarded, (2) unsubscribe only if there are no outstanding notifications, and (3) if there are outstanding notifications wait until they are processed and discarded and then unsubscribe.

process_passive, process_active primitives

These two primitives are intended to be called from a Pre constraint and to terminate the Pre constraint in which they occur. The primitives call the method of the current object passing to it a pointer to the block of parameters, and the address of the Post constraint. The called method unmarshalls the parameters, executes the application code, and after that calls the Post constraint. In the case of *process_active* a new thread is created to execute the method.

The "passive" attribute means that the object allows an external thread of control to "enter" into the object and execute the given method (i.e., the object appears to be passive). In the case of *process_active*, the object allows a new thread of control to be created to execute the given method (optionally, a priority can be specified for this thread). Note that for an object to be "passive" it is not sufficient that it uses *process_passive* in its Pre constraints. In addition to this the object's environment must never attempt concurrent deliveries, i.e., the ECOlib must not offer in parallel two event notifications to the same object. In other words, being passive is not a local property of an object, it is a property of an object plus its environment. The ECOlib satisfies this requirement, i.e., it never attempts two deliveries to the same object in parallel. This allows an object to have a full control over the level of concurrency within the object.

enqueue, dequeue primitives

The *enqueue* primitive is intended to be called from a Pre constraint to enqueue the current ENP on the queue of waiting ENPs of the current method. A call to *enqueue* s intended to terminate the processing of the Pre constraint in which it occurs. The enqueued ENP will be processed later, after it is dequeued by calling the *dequeue* primitive.

The *dequeue* primitive is intended to be called from a Pre or from a Post constraint. It dequeues the first ENP from the queue of waiting ENPs of the named method of the current object. This ENP is enqueued (according to its priority) into the queue of ready ENPs for this method.

discard_single, discard_all primitives

These two primitives are intended to be called from a Pre constraint to explicitly discard the current ENP. They will both terminate the processing of a Pre constraint. The *discard_single* primitive discards the current ENP for the current method of the current object. The same ENP remains remembered by the ECOLib to be delivered to other destinations. The *discard_all* primitive removes the current ENP for all the destinations which have not already been delivered the same ENP. If some destination has already been delivered this ENP (and possibly enqueued the ENP for later processing), the ENP of this destination is not discarded.

An example which illustrates this is: an event happens and a number of objects are interested to be informed about this. Some object is told about the event, it does some processing, and the event notification for this object is discarded. Some other object is told about the same event and it decides to enqueue the notification for later processing (conceptually this notification is now in the object's "private space"). Finally some other object is told about the same event and it calls *discard_all* from a Pre constraint. This has the effect that the notification of this event for this object and for all the other objects which have not already seen this notification are discarded.

Note that there is an implicit *discard_single* after an event notification is delivered, and after the corresponding Post constraint is run.

3.2.2.1 Priorities

The users can indicate to the ECOlib the priority of an event and priority of an event announcement. A priority is an integer from the $[0, \ldots, MAXPRI]$ range, where 0 denotes the smallest and MAXPRI denotes the highest priority (a priority may be "not used", which is denoted by a special value NOPRI). The next paragraphs summarise when a priority may be specified, the meaning of these priorities, and the default priority in each case (i.e., the priority value chosen if the user specifies NOPRI).

- An event can be given priority when *create_event* is announced. If not given, the event is given the lowest priority by default. This priority is inherited by the event announcements (if it is not overridden).
- An event announcement can be given priority when the announcement is made. If not given, the announcement is given the priority of the event by default. This priority indicates to ECOlib how to order all the event notifications, and as a special case, all the notifications of the same event bound to the same destination.
- *process_active* can specify a priority for the thread which is to execute the method. If not given, the thread inherits the priority of the event by default. This priority can be used by the thread scheduler[3] to determine the order in which the threads are executed.

3.2.3 The predefined events

There is a small number of predefined events, their names and their intended usage are given below.

- *create_class*, announced when a new class is created to inform the ECOlib about this new class,
- *destroy_class*, announced when an existing class is deleted,
- *create_object*, announced when a new object is created to inform the ECOlib about this new object,
- *destroy_object*, announced when an existing object is deleted,
- *create_event*, announced when a new event is created to inform the ECOlib about the name and parameters of this new event,
- *destroy_event*, announced when an existing event is deleted (it is not possible to delete a predefined event),
- *error*, announced when an error condition has been detected.

There are also some predefined events internal to the ECOlib. Most of the above predefined events are announced by the ECOlib client to inform the ECOlib that a class or object instance or event is created or destroyed. The *error* event is announced by the ECOlib when some error has been detected.

The ECOlib creates neither objects nor classes — it is up to the user to do the necessary work (for example, to allocate the space for an object and initialise some data and control information, like class/object identifier), and to inform the ECOlib about this. The ECOlib handles these predefined events and initialises its internal state based on the information passed to it.

The following text describes the above predefined events and two of the ECOlib internal events (announced by the ECOlib). For each of the predefined events we give the event name and parameters. Users can create their own events, different from the predefined events, and use

[3] Assuming the underlying thread manager supports prioritised threads.

the ECOlib to announce them, subscribe to them, etc. The ECOlib has internal data structures similar to the structures given below (it adds some extra fields to these structures, for example the links between the structures, and the locks used to protect the structures from the concurrent accesses).

create_class event

This predefined event is announced when a new class is created. The event parameter is the *class descriptor* (CD) shown below.

```
struct cd {             /* class descriptor */

        char* name_cd;  /* class name */
        int id_cd;      /* class ID */

        md md_cd[M1];   /* method descriptors */
        cond notify_cd[M2]; /* notify constraint descriptors */
        cond pre_cd[M2]; /* pre constraint descriptors */
        cond post_cd[M2]; /* post constraint descriptors */
        char* ine_cd[M3]; /* names of inevents */
        char* oute_cd[M3]; /* names of outevents */
}
```

The *inevents* and *outevents* are the events which the class is prepared to handle and to announce (i.e., the names of events which the class may announce, and to which it may bind its methods). These events have to be known to ECOlib when *create_class* is announced. A class descriptor contains a *method descriptor* (MD) for each of the class methods, and a *constraint descriptor* (COND) for each of the class constraints (Notify, Pre, and Post constraints). $M1$, $M2$, and $M3$ are the ECOlib configuration parameters. $M1$ is the maximum number of methods per class, $M2$ is the maximum number of each of Notify/Pre/Post constraints per class, and $M3$ is the maximum number of each of inevents/outevents per class.

```
struct md {             /* method descriptor */

        char* name_md;  /* method name */
        void* add_md;   /* method code memory address */
        pd pd_md[M4];   /* parameter descriptors */
}
```

A method descriptor contains a parameter descriptor (PD) for each of the method parameters. $M4$ is the maximum number of parameters per method.

```
struct pd {             /* parameter descriptor */

        char* name_pd;  /* name */
        int size_pd;    /* size */
        int type_pd;    /* type ID */
}

struct cond {            /* constraint descriptor */

        char* name_cond; /* name */
        void* add_cond;  /* code memory address */
}
```

The *type* of a method parameter is an identifier passed to the ECOlib. It is used when a method-event binding is esatblished to check if the method and event signatures match (the ECOlib does not assign any meaning to these type identifiers and is only interested in the total size of the method/event parameters, in addition to testing if two type identifiers are equal).

destroy_class event

This predefined event is announced when an existing class is destroyed. The event paramater is the name of the class which is destroyed. An implementation of the event handler for this event may: (1) destroy any record of this class only if currently there are no instances of the class, or (2) destroy any record of the class in any case. If the second option is used and there are some instances of the deleted class, this may cause an error condition to be detected when the information from the deleted class is required by these instances.

create_object event

This predefined event is announced when an object is created. The event parameter is the *object descriptor* (OD) shown below plus the name of the object's class.

```
struct od {             /* object descriptor */

        int objid_od;   /* ID */
        mid mid_od[M1]; /* method descriptors */
}


struct mid {            /* object method descriptor */

       void* add_mid;   /* code memory address */
       ebd ebd_mid[M5]; /* bindings to events */
}


struct ebd {            /* method-event binding descriptor */

        void* notify_ebd; /* notify address memory address */
        void* pre_ebd;    /* pre constraint memory address */
        void* post_ebd;   /* post constraint memory address */
}
```

The ECOlib maintains for each object and for each method of the object the bindings between the method and events. This information is held in the event binding descriptor (EBD) for each of the events to which the method is subscribed. An EBD contains information about the constraints associated with the binding. The configuration parameter $M5$ is the maximum number of events to which a single method may be simultaneously bound.

destroy_object event

This predefined event is announced when an existing object is destroyed. The event parameter is the ID of the object which is destroyed. Similar to *destroy_class*, an implementation of the handler for this predefined event may: (1) destroy the record of this object only if currently there are no bindings of the object's methods to any events, or (2) destroy the record of this object only if there are no outstanding event notifications for this object, or (3) destroy the record of this object in any case, discarding any possible outstanding event notifications.

create_event event

This predefined event is announced when an event is created, i.e., when a description of a new event which may be announced, subscribed to etc., is created. The event parameter is the *event descriptor* (ED) shown below.

```
struct ed {             /* event descriptor */

        char* name_ed;  /* event name */
        int size_ed;    /* size of event params */
        int pri_ed;     /* event priority */
        pd pd_ed[M4];   /* parameter descriptors */
}
```

An event descriptor contains a parameter descriptor (PD) for each of the event parameters. The ECOlib maintains for each event the bindings between the event and objects (their methods). The event priority field of the event descriptor indicates the importance of the event relative to all the other events. If this field has value "not used" the lowest priority is used by default. All the occurrences of an event, which are to be delivered to a single destination, can be ordered among themselves by giving them appropriate priorities.

destroy_event event

This predefined event is announced when the description of an existing event is to be destroyed. The event paramater is the name of the event which is destroyed. Similar to *destroy_class* and *destroy_object*, an implementation of the handler for this predefined event may: (1) destroy the record of this event only if currently there are no bindings to this event, or (2) destroy the record of this event only if there are no outstanding notifications of this event, or (3) destroy the record of this event in any case, discarding any possible outstanding event notifications. In the last two cases the possible bindings to the deleted event should also be discarded.

error event

This event is announced by ECOlib whenever some error condition is detected. The users subscribe to this event if they wish to be told about a specific error. The event parameters are: an error code and one or two messages which give more details about the error condition. Presently, the error code can be:

- no such event,
- no such method,
- no such binding.

In the first case the additional parameter is the event name, in the second case it is the method name, and in the last case the additional parameters are event name and method name.

subscribe_internal event

This is an internal ECOlib event announced when the previously described *subscribe* primitive is used. The event parameters are:

- object ID and method name. The object ID is always of the current object (the object which invoked *subscribe*); the method name does not have to be of the current method, but it does have to be of the current object.

- event name. The name of the event to which the method subscribes.
- Notify constraint name, Pre constraint name, and Post constraint name. These names are optional, and if given have to be local to the class of the current object.

unsubscribe_internal event

Similar to *subscribe_internal* this is an internal ECOlib event, announced when the *unsubscribe* primitive is invoked. The event parameters are: object ID and method name (the same restrictions are valid here as in the case of *subscribe_internal*), and event name.

3.3 Summary

This chapter describes the ECOlib interface and the assumptions about the environment in which this library is used. It is obvious that in some cases there may be tighter coupling between the ECOlib code and the rest of the VOID shell. For example, in some cases a method address or an event identifier may be passed to a primitive instead of a character string being passed a for method name or event name. In other cases, it may be known that no object will ever use *process_active*, and that ECOlib can relax some of its assumptions about the possible concurrent accesses to some data structures. This would allow ECOlib to be implemented more efficiently.

The ECOlib described in this chapter is being implemented for a single address space, multi-threaded environment. In future it will be extended to support multiple address spaces and multiple nodes connected over a network.

Chapter 4

The `VOID` Libraries

4.1 Introduction

The VOID libraries are a a key part of the `MOONLIGHT` strategy for improving productivity in the development of video-game and virtual world programs. The libraries provide a unified and consistent interface to the various kinds of functionality that are required, such as two and three dimensional graphics, input control, detection of collision between entities in the virtual world and so on.

The libraries are one of three parts to the unified solution that TCD is proposing, the other parts being:

- an Entity Editor tool capable of automatic generation of application code from a graphical notation (statecharts);
- run-time support, called ECO, for event-based programming.

In the text below we describe the relationship between the VOID libraries and these other components.

Relationship to Entity Editor One of the key points in our approach to rapid prototyping of video games and virtual worlds is the use of a graphical notation to specify the behaviour of the entities. The VOID libraries are the key to allowing these specifications to become prototypes: they provide the code that is used to provide functionality for entities. By framing the various underlying software packages (such as GUL, SUL, etc) in a consistent, object-oriented C++ library the Entity Editor tool will be able produce *working* programs *automatically*.

Relationship to ECO The VOID libraries are basically independent of (but compatible with) the ECO library, at least in this initial release. In effect the VOID libraries and the ECOlib form twin supports for the Entity Editor. This is because programs written using statecharts need the event support provided by the ECOlib. If these event-based programs are video-games then they will also require the functionality provided by the VOID libraries.

Relationship to ECOsim In this release of the libraries we include a library called ECOsim, which contains some simple class-based support for event-based programming. The purpose of this library is to allow development of programs using the libraries in advance of completion of the ECO model.

The class support is neither particularly efficient nor fully-featured, but it does offer a significant advantage over programming in straight C++: namely that it is *not* straight C++. Programs written using the standard models of invocation and named addressing of C++ will have a very different structure to those developed using events. Therefore, if code developed using the early versions of the libraries is to be of any use subsequently it should be developed using an event-based approach.

4.2 Contents

This chapter provides a description of the structure and functionality of the libraries as well as a snapshot of the interfaces of the current release (the libraries themselves are undergoing constant extension). Included in Appendix B is a description of the ECOsim library and some examples of its use.

4.3 Structure of the libraries

There are both quite a number of individual libraries and (potentially) several instances of each library, arising from two motivations:

- `MOONLIGHT` has several target platforms;
- the functionality required for videogames and virtual worlds has several distinct parts (sound, graphics, video, entity interaction etc.)

4.3.1 Ramifications of multiple target platforms

The desire to support multiple hardware platforms may make it necessary to have several versions of any given library. This is more than a matter of using different compilers. If all the code is platform independent then the different versions would indeed differ only in the compiler. In practice, however, some of the the code will be platform specific *to take advantage of the hardware*. So for example, if the target platform for a given application is a PC which contains the `MOONLIGHT` board then the program should be linked with a library which drives this board. If, on the other hand the target platform is a PC without any graphics hardware then the same program could be linked with a library which provides software emulation for the graphics functions.

4.3.2 Ramifications of functional divisions

The second partitioning influence on the libraries is the desire to pick and mix functionality on a per application basis. For example, in an application in which the sound is relatively uncomplicated then one would wish to avoid using a heavyweight sound library.

It would of course be possible to create a single, monolithic library with all the functionality that could ever be used in a video game or virtual world, but it would not be very good software engineering, due to the increased size and, inevitably symbol name clashes. Especially in a video game where the cost of the unit is strongly related to the size of the memory and where speed is also extremely important. Of course, even in a monolithic library only the necessary object files are linked, but then programmer must rely on the library's author and, more importantly maintainers, to maintain the internal divisions.

4.4 Platform and products

Naturally, not all of the libraries will exist on every platform because some are intrinsically platform specific. To complicate matters further the same library may have different names on different platforms due to the restrictions of the OS or the compiler.

Definition The concept of a "product" is borrowed from [35] and describes a particular output of a compilation or link process. Every library in the VOID system is a product, some libraries represent more than one product because they are present on several platforms.

The relationship between platforms and products for some representative libraries in the VOID system is illustrated by Table 4.1 below. The table shows the five directories associated with the production of eight graphics library products on (currently) three platforms. To these will later be added platforms for the `MOONLIGHT` arcade board and possibly other MS-DOS or UNIX compilers.

Product dir	product(s)	platforms	description
graphics/gl.lib	libvoidgl.a	irix4cc	C++ wrappers for gl
graphics/gulsoft.lib	libvoidguls.a libvguls.lib libvoidguls.a	irix4cc watcom (TWS)	C++ wrapper for gul software-only versions
graphics/gulhard.lib	libvgulh.lib libvoidgulh.a	watcom (TWS)	C++ wrapper for gul with hardware assist
graphics/ABCs.ini	(headers)	(shared)	C++ header files for all versions of library voidg
graphics/ABCs.lib	libvoidg.a libvoidg.lib	irix4cc watcom	base class code for void graphics
input/ABCs.ini	(headers)	(shared)	C++ header files for input control

Figure 4.1: VOID libraries and platform: the current status

Managing this source is a complex business which requires strict demarcation between platform dependent and platfrom independent source. This separation is integrated with our OO approach through the use of a library of Abstract Base Classes (ABCs) which enforce interfaces and which represent an abstract framework which the platform specific code implements.

4.5 Functionality

As mentioned elsewhere (§4.1) an important intended client of the VOID libraries is the (code generated by the) Entity Editor tool. The libraries should ideally provide everything that the user of the Entity Editor does not. There are two aspects to the functionality required by this machine generated code. Firstly the entities will require a basic set of functions which will provide the "vocabulary" that is usable for the specification of event handlers in the Entity Editor. Secondly, the application will obviously require much functionality beside that which is held in the game entities: such things as graphics libraries and sound drivers.

A distinction can therefore be drawn between the means in which the libraries functionality is brought to the application, either by inheritance or in a client-server fashion. This amounts to the same distinction as described in previous documents[17][57]) between Standard Objects and Generic Classes.

Standard Objects include all those classes which are necessary to provide the ancilliary functionality which is used in the application but which is not part of any Entity. This includes functionality that is outside of all Entities (eg. I/O, 3D rendering) and functionality that exists *between* Entity instances (eg. perception, collision etc).

Generic Objects allow access to library functionality through invocations of Base Class methods. This allows the actions of these Game Entities to be written using these Base Class methods.

Generic classes thus provide small, comprehensible interfaces to the Standard Objects. Comprehensibity is bought at the price of restricting the expressive power of the Standard Objects in certain ways. These restrictions do not, however, impede the application programmer because the Generic Classes are tailored to provide the most useful functionality for writing video games and virtual worlds.

This division is (only) conceptual: it is useful for categorisation and description. It also marks an important division of learning: the application programmer need only know about the Generic Classes. However it should be noted that *at the source code level* the two groups are quite tightly bound together. This is because the Generic Objects act as interfaces to the more complicated Generic Objects, and the implementation of the Generic Classes is therefore strongly related to the implementation of the Standard Objects.

Where the classes provided prove insufficient the solution is to add a new Generic Class to the library rather than to "work around" the existing Generic Classes to get at the Standard Objects directly. This method promotes re-use and program correctness, without impeding a rapid development because it is basically a stuctural change not a procedural one. The code must be written in any case, but by writing it into the library it is available for re-use.

4.6 Design diagrams

4.6.1 Using inheritance for multi-platform support

Figure 4.2 shows the pattern of inheritance in this library: each Abstract Base Class (ABC) has (at least one) concrete child class. There is one concrete class for each platform that must be supported, in this diagram we show the child classes which support the GUL version of the VOID graphics library, and two unnamed alternative implementations.

All of these child-classes must, of course, conform to the interface specified in the ABCs (although they are free to extend it). This means that applications written to use the ABCs may be ported to other platforms without change to their code, and that cross-platform development/prototyping is possible.

4.6.2 Generic types and simplified interfaces

Figure 4.3 shows some of the complex inter-relations between the classes that make up one of the VOID libraries, the GUL implementation of the graphics library. It is important to emphasise that the complexity of this diagram is hidden from VOID clients, through the divsion between Standard Objects and Generic Classes.

In this library the Generic Class is `GraphicObject`, and its concrete class is `GUL_GraphicObject`. It is only this class that VOID library users and client code should have to deal with, as it hides the complexity of the Standard Objects. This can be seen in Figure 4.4, in which the Abstract Base Class `GraphicObject` and its GUL specific child-class `GUL_GraphicObject` have been pulled down below the other classes to show the separation between Generic Classes and Standard Objects.

4.7 Development Strategy

Our approach to developing these libraries has been a synthesis of three approaches:

- object-oriented design and programming;
- encapsulation of existing libraries;
- parallel development of applications.

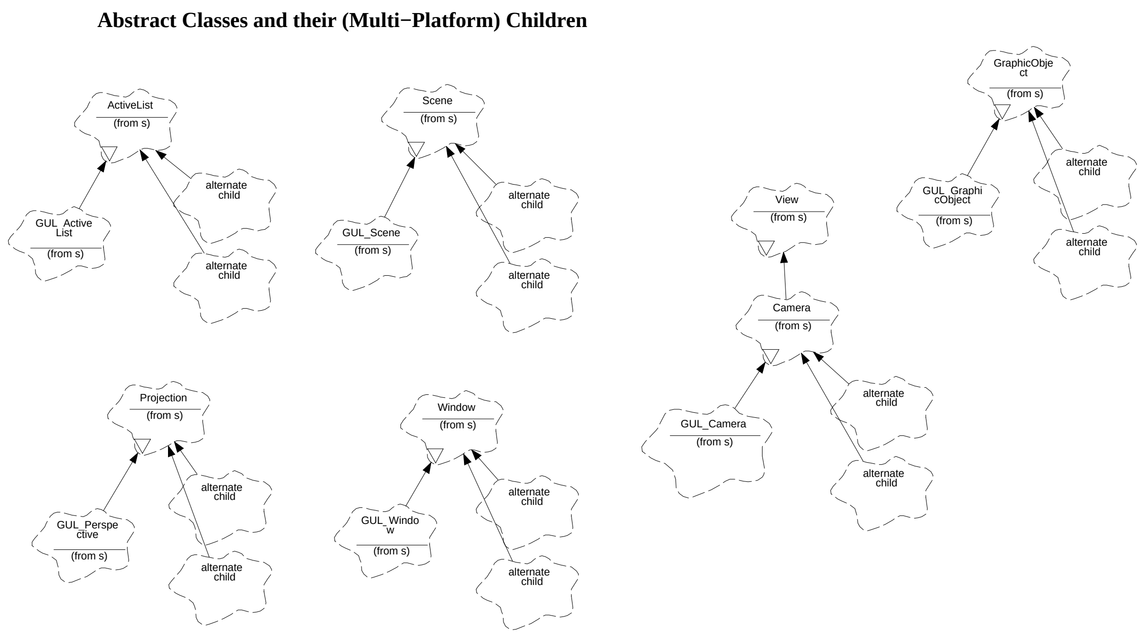


Figure 4.2: Inheritance in the graphics libraries

4.7.1 Object oriented design and programming

In addition to doing the design work using OOD, the implementation of the libraries makes extensive use of Object-Oriented techniques:

- Abstract Base Classes have been used to hold the platform-independent interface, with platform-specific incarnations of these classes providing the actual code. This ensures a consistent interface and functionality for the libraries across platforms
- Class data is entirely encapsulated in all the classes in the libraries and can only be accessed through the functions of the class interface.
- There are no global variables.
- Functionality that is required for applications is accessed through inheritance of the appropriate base Generic Class from the library. The interface to the Generic class in question then insulates the programmer from both the internals of the library and from some of the complexity of its structure.

4.7.2 Encapsulating existing libraries

One very important role of the VOID libraries is in hiding the complexities of other software components of the project and giving a consistent interface to these other components. At present the ~~only external~~ library that has been available to be included is the Graphic Ultra Light (GUL) library for 3D graphics (written by Caption). We anticipate adding the Sound Ultra Light interface as soon as it is available.

Example The GUL library is written in the C language, with a traditional non-OO API. We have written C++ code (conforming to the VOID graphics library OO design) which *wraps*[1] this

[1]this involves a lot more than just call-forwarding, see code for details

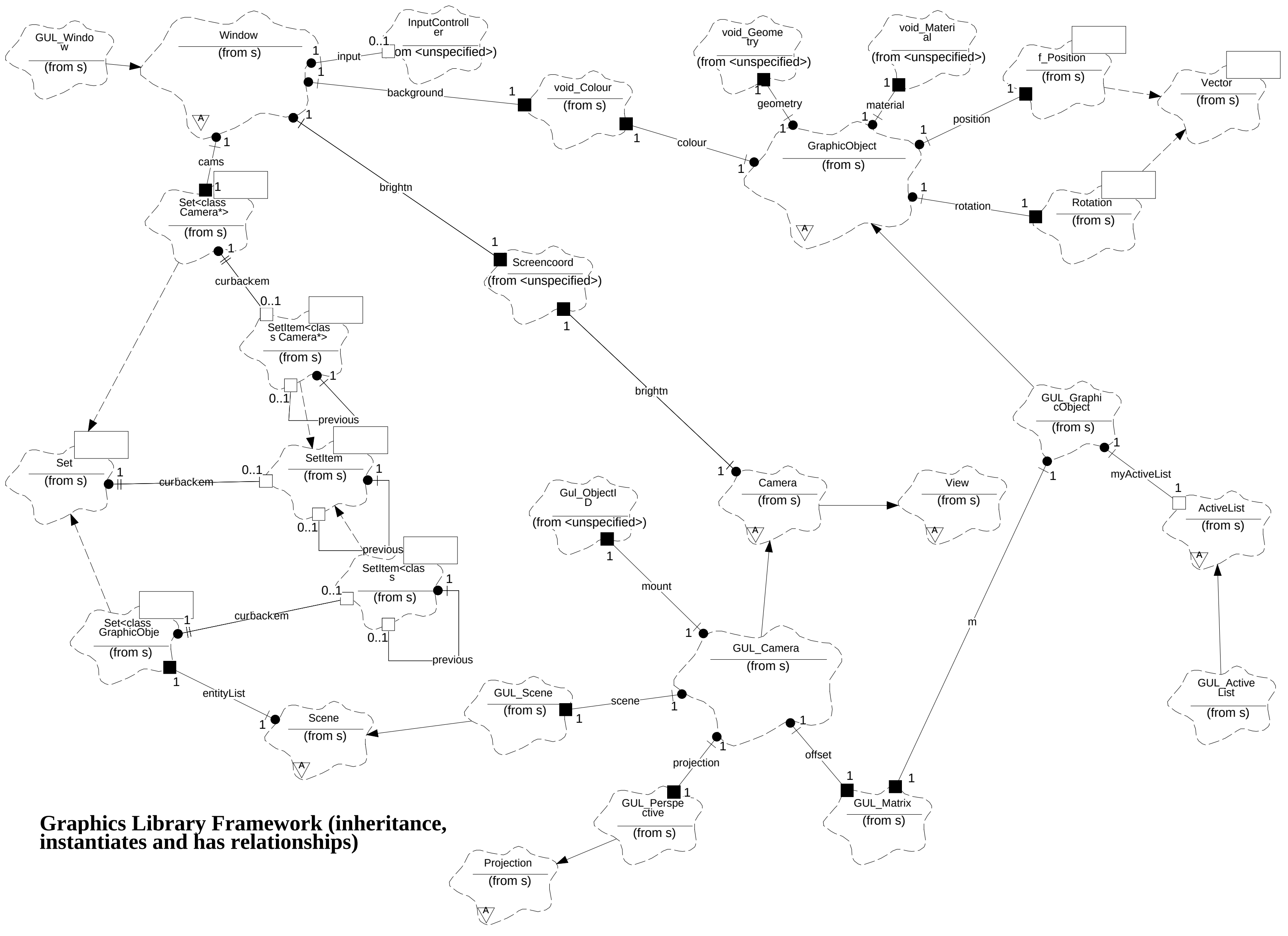


Figure 4.3: Class relationships in the graphics framework

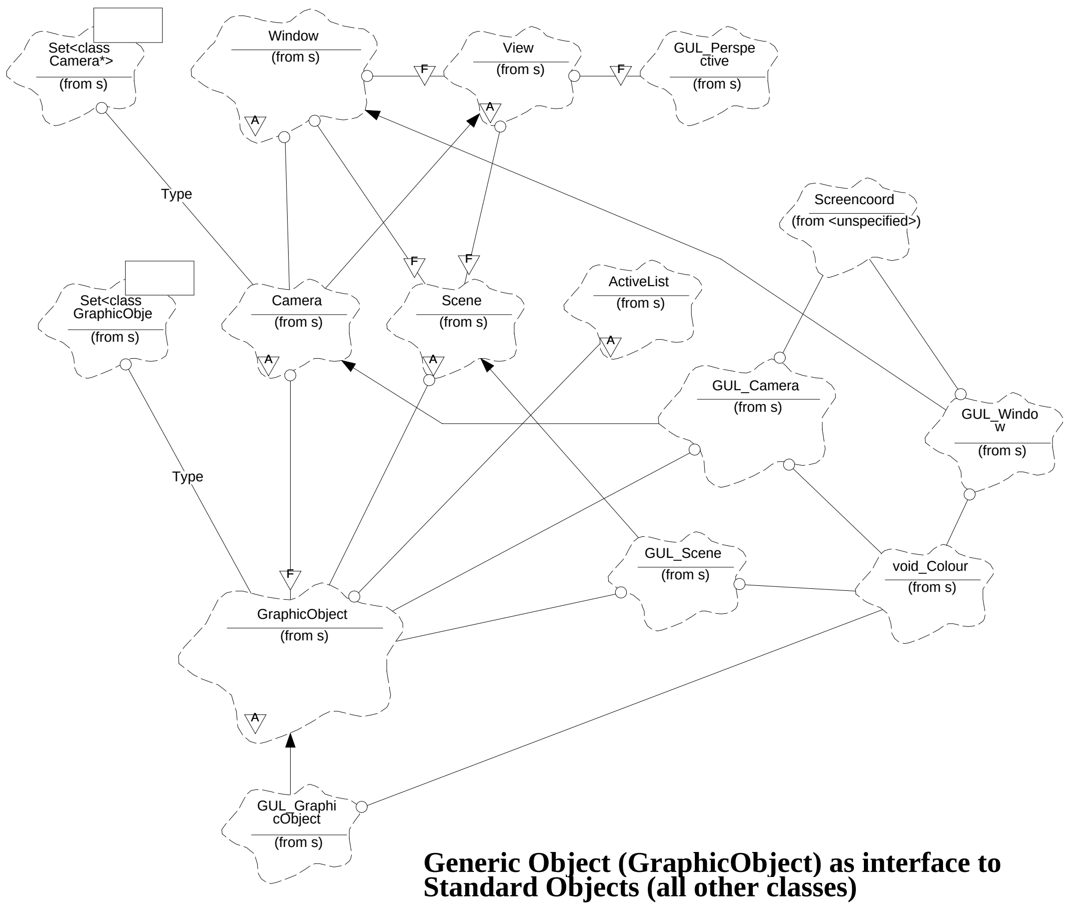


Figure 4.4: Standard objects/Generic Classes

C API and allows its functionality to be accessed through the Generic Class `GUL_GraphicObject`. This class is a sub-type of `GraphicObject` which is an Abstract Base Class from the VOID graphics library.

4.7.3 Applications

In tandem with the development of the libraries we have been developing an application which is a version of the arcade game "BattleZone", itself reincarnated recently by NamCo as "CyberSled". Developing this application serves two purposes. Firstly it greatly facilitates validation of the functionality of the library. Secondly, where functionality used in the application is *not* present in the library (or the library design) we are able to consider whether this functionality is not in the libraries through omission or because it is application specific.

Example Consider a situation that might arise in writing a virtual world simulation. The application programmer wishes to do collision detection with some three-dimensional shapes, which are complex in terms of numbers of primitives. It might turn out that the libraries' collision support was infeasibly slow with such complex shapes, but that a faster algorithm could be found, which made use of some domain-specific simplification (perhaps these complex pieces are being moved in simple axial-parallel ways).

Once the application programmer had developed this code it could be moved to the collision library as another policy type, embodied in another Generic Base Class. Subsequent programmers would then have access to this functionality.

4.8 Summary

This chapter has described the development approach, the design and the software architecture of the VOID libraries.

Appendix A

Interfaces to the libraries

A.1 Graphics classes

A.1.1 Abstract Base Classes for graphics

```
//-*-c++-*-

#ifndef ACTIVELIST_HH
#define ACTIVELIST_HH

#include "Geometry.hh"
#include "code_std.hh"

// defines generic interface for active lists (of objects to be rendered),
// initially used to support the GUL active list, later this functionality
// is to be added to GL version of VOID also
ABSTRACT_CLASS ActiveList {
public:
    ActiveList() {}  // no ctor as yet
    virtual void addToList(void_Geometry new_obj) = PURE_VIRTUAL;
    virtual void removeFromList(void_Geometry dead_obj) = PURE_VIRTUAL;
};

#endif
```

Figure A.1: ActiveList.hh

A.1.2 Graphics class instantiations for GUL

These definitions serve for both both software and hardware versions of GUL on all platforms.

```
//-*-c++-*-

#ifndef GEOMETRY_HH
#define GEOMETRY_HH

typedef short int void_Material;

#ifdef USING_GUL
typedef short int void_Geometry;
#endif

#ifdef USING_GL
typedef Object void_Geometry;
#endif

#endif
```

Figure A.2: Geometry.hh

```
//-*-c++-*-

#ifndef POSITION_HH
#define POSITION_HH

#include <math.h>
#include "Vector.hh"

typedef Vector<float> f_Position;

#endif
```

Figure A.3: Position.hh

```
//-*-c++-*-

#ifndef PROJECTION_HH
#define PROJECTION_HH

#include "code_std.hh"

// The projection virtual base class.
/***************************************************************************/
ABSTRACT_CLASS Projection {
/***************************************************************************/
public:
    virtual void apply() = PURE_VIRTUAL;
    virtual void remove() = PURE_VIRTUAL;
};


#endif
```

Figure A.4: Projection.hh

```
//-*-c++-*-

#ifndef ROTATION_HH
#define ROTATION_HH

#include <math.h>
#include "Vector.hh"
#include "gl.h"

typedef Vector<Angle> Rotation;

#endif
```

Figure A.5: Rotation.hh

```
//-*-c++-*-

#ifndef VIEW_HH
#define VIEW_HH

#include "code_std.hh"

/*************************************************************************/
ABSTRACT_CLASS View {
/*************************************************************************/
friend class Window;
public:
    virtual void snapshot() = PURE_VIRTUAL;
};

#endif
```

Figure A.6: View.hh

```
//-*-c++-*-

#ifndef CAMERA_HH
#define CAMERA_HH

#include "GraphicObject.hh"
#include "Projection.hh"
#include "Scene.hh"
#include "View.hh"

/****************************************************************************/
class Camera : public View {
/****************************************************************************/
protected:
        Screencoord top, bottom, left, right;

public:

       Camera(Screencoord, Screencoord, Screencoord, Screencoord);

//      ~Camera();

       virtual void add(GraphicObject *go) = PURE_VIRTUAL;
       // has to be virtual cos scene is not a component of the base class,
       // and it currently isn't because it takes different params in
       // the two variants. This may be fixable later.

       virtual void set() = PURE_VIRTUAL;
       virtual void snapshot() = PURE_VIRTUAL;
       virtual void setMount(GraphicObject *m) = PURE_VIRTUAL;
       virtual void Offset(f_Position &new_offset) = PURE_VIRTUAL;
};

#ifndef MOONLIGHT_OUTLINE
#define INLINE inline
#include "Camera.icc"
#endif

#endif
```

Figure A.7: Camera.hh

```
//-*-c++-*-

#ifndef SCENE_HH
#define SCENE_HH

#include "code_std.hh"
#include "Set.hh"
#include "GraphicObject.hh"

/***************************************************************************/
ABSTRACT_CLASS Scene {
/***************************************************************************/
friend class Window;
friend class View;

protected:
    Set<GraphicObject *> entityList;

public:
    Scene();
    ~Scene();

    virtual void add(GraphicObject *) = PURE_VIRTUAL;
    virtual void remove(GraphicObject *) = PURE_VIRTUAL;
};

// no inline functions so far for Abstract class Scene
#ifndef MOONLIGHT_OUTLINE
#define INLINE inline
//#include "Scene.icc"
#endif

#endif
```

Figure A.8: Scene.hh

```
//-*-c++-*-

#ifndef WINDOW_HH
#define WINDOW_HH

#include "code_std.hh"
#include "InputController.hh"
#include "Camera.hh"

/*************************************************************************/
ABSTRACT_CLASS Window {
/*************************************************************************/
friend class GraphicDevice;
protected:
    Screencoord top, bottom, left, right;
    long windowHandle;
    char *windowName;
    void_Colour background;
    Set<Camera *> cams;
    InputController * input;                    // shouldn't be part of the window

    virtual void draw() = PURE_VIRTUAL;
public:
    Window(char * n, void_Colour c, Screencoord t,
           Screencoord b,Screencoord l,Screencoord r);

    ~Window();

    void setInputControl(InputController *);
    void add(Camera * v);
    void remove(Camera * v);
};

#ifndef MOONLIGHT_OUTLINE
#include "Window.icc"
#endif

#endif
```

Figure A.9: Window.hh

```
//-*-c++-*-

#ifndef GRAPHICOBJECT_HH
#define GRAPHICOBJECT_HH

#include "code_std.hh"
#include "ActiveList.hh"
#include "Geometry.hh"
#include "rgbColour.hh"
#include "Position.hh"
#include "Rotation.hh"

/***************************************************************************/
ABSTRACT_CLASS GraphicObject {
/***************************************************************************/
friend class Camera;
protected:                                                                        // data
    f_Position position;
    Rotation rotation;
    void_Colour colour;
    void_Material material;
    void_Geometry geometry;

protected:                                                                     // methods
    void setGeometry(void_Geometry obj);
    void setColour(void_Colour c);
    void setMaterial(void_Material m);

    void setPosition(f_Position p);
    void setRotation(Rotation r);

    Angle xRot();
    Angle yRot();
    Angle zRot();

    float xPos();
    float yPos();
    float zPos();

public:                                                                        // methods
    GraphicObject(f_Position &, Rotation &, ActiveList &, void_Geometry &, void_Colour,
void_Material);
    virtual void makeActive() = PURE_VIRTUAL;   //  will be implemented here RSN(TM)
    virtual void makeInactive() = PURE_VIRTUAL; //  will be implemented here RSN(TM)
    virtual void render() = PURE_VIRTUAL;
    void_Geometry getGeometry();
};

#ifndef MOONLIGHT_OUTLINE
#define INLINE inline
#include "GraphicObject.icc"
#endif
```

```
#endif
```

Figure A.10: GraphicObject.hh

```
//-*-c++-*-

#ifndef GUL_ACTIVELIST_HH
#define GUL_ACTIVELIST_HH

#include "ActiveList.hh"

#include "GUL_Proto.hh"
#define GUL_MAXOBJ 100

class GUL_ActiveList : public ActiveList {
// abstraction for the GUL active list of objects to be rendered
protected:
    int count;                                              // number of active objects
    short list[GUL_MAXOBJ];                                               // our list
    short copy[GUL_MAXOBJ];                                              // GUL's list
protected:                                                     // member functions
    void updateGUL();
public:
    GUL_ActiveList();
    virtual void addToList(void_Geometry new_obj);
    virtual void removeFromList(void_Geometry dead_obj);
};


#endif
```

Figure A.11: GULActiveList.hh

```
//-*-c++-*-

#ifndef GUL_CAMERA_HH
#define GUL_CAMERA_HH

#include "Camera.hh"
#include "GUL_Projection.hh"
#include "GUL_Scene.hh"
#include "gl.h"

/****************************************************************************/
class GUL_Camera : public Camera {
/****************************************************************************/
protected:
      Gul_ObjectID mount;                          // identifier not object or pointer
      GUL_Perspective projection;
      GUL_Scene scene;
      GUL_Matrix offset;

public:

     GUL_Camera(Screencoord, Screencoord, Screencoord, Screencoord,
              Angle, float, float, float,                        // for projection
              float , float, f_Direction, void_Colour,               // for scene
              f_Position &);                                          // offset

     ~GUL_Camera();
     void setMount(GraphicObject *m);
     void set();
     void Offset(f_Position &new_offset);
     void snapshot();

     virtual void add(GraphicObject *go);                  //{ scene.add(go); }
};

#ifndef MOONLIGHT_OUTLINE
#define INLINE inline
//#include "GUL_Camera.icc"
#endif

#endif
```

Figure A.12: GULCamera.hh

```
//-*-c++-*-

#ifndef GUL_GRAPHICOBJECT_HH
#define GUL_GRAPHICOBJECT_HH

#include "GUL_Matrix.hh"
#include "GraphicObject.hh"

typedef short int Material;

/***************************************************************************/
class GUL_GraphicObject : public GraphicObject {
/***************************************************************************/
friend class Camera;
protected:                                                              // data
    GUL_Matrix m;
    ActiveList &myActiveList;

public:                                                              // methods
    GUL_GraphicObject(f_Position &, Rotation &, ActiveList &, void_Geometry &, void_Colour,
Material);
    virtual void makeActive();               // will migrate to the base class in next pass
    virtual void makeInactive();             // will migrate to the base class in next pass
    virtual void render();
};

#ifndef MOONLIGHT_OUTLINE
#include "GUL_GraphicObject.icc"
#define INLINE inline
#endif

#endif
```

Figure A.13: GULGraphicObject.hh

```
//-*-c++-*-

#ifndef GUL_MATRIX_HH
#define GUL_MATRIX_HH

#include "Position.hh"
#include "Rotation.hh"
#include <iostream.h>

extern "C" void exit(int);

class GUL_Matrix {
 protected:
    float m[12];
    static float error;
 public:
    GUL_Matrix();
    GUL_Matrix(float f1,float f2,float f3,float f4,
           float f5,float f6,float f7,float f8,
           float f9,float f10,float f11,float f12);
    GUL_Matrix(const GUL_Matrix &v);
    GUL_Matrix &operator=(const GUL_Matrix &v);
    float &operator[](unsigned int i);
    GUL_Matrix invert();
    GUL_Matrix operator*(const GUL_Matrix &v);
    GUL_Matrix rotateX(Angle a);
    GUL_Matrix rotateY(Angle a);
    GUL_Matrix rotateZ(Angle a);
    GUL_Matrix translate(f_Position &p);
    friend ostream& operator<<(ostream&, GUL_Matrix &);
};

#ifndef MOONLIGHT_OUTLINE
#include "GUL_Matrix.icc"
#define INLINE inline
#endif

#endif
```

Figure A.14: GULMatrix.hh

```
//-*-c++-*-

#ifndef GUL_PROJECTION_HH
#define GUL_PROJECTION_HH

#include "Projection.hh"
#include "gl.h"

/****************************************************************************/
class GUL_Perspective : public Projection {
/****************************************************************************/
friend class View;
protected:

public:
    GUL_Perspective(Angle fy, float a, float n, float f);
    void apply();
    void remove();
};

#ifndef MOONLIGHT_OUTLINE
#include "GUL_Projection.icc"
#define INLINE inline
#endif

#endif
```

Figure A.15: GULProjection.hh

```
#include "GUL_Matrix.hh"
typedef Vector<float> f_Direction;
typedef short int Gul_ObjectID;

extern "C" {
#include "Gul.h"
void Gul_SetActiveList(short *, short);
void Gul_SetCameraAngle(double);
void Gul_GetCameraAngle(double*);
void Gul_SetCameraZClip(double);
void Gul_SetCameraDepth(double);
void Gul_SetAmbientPower(double);
void Gul_SetLightPower(double);
void Gul_CreateObject(short *,OBJ *);
void Gul_ModifyActiveList(CMD *, short);
void Gul_SetLightDirection(f_Direction *);
void Gul_GetObjectMatrix(short, GUL_Matrix *);
void Gul_SetObjectMatrix(short, GUL_Matrix *);
void Gul_SetViewportColor(COLOR);
void Gul_SetCameraMatrix(GUL_Matrix *);
void Gul_GetCameraMatrix(GUL_Matrix *);
void Gul_Render();
void Gul_SyncRender();
void Gul_SwapFrameBuffer();
void Gul_Open(short, short);
void Gul_InitObject(short);
}
```

Figure A.16: GULProto.hh

```
//-*-c++-*-

#ifndef GUL_SCENE_HH
#define GUL_SCENE_HH

#include "Scene.hh"
#include "GUL_Proto.hh"
#include "gl.h"
#include "rgbColour.hh"

/*************************************************************************/
class GUL_Scene : public Scene {
/*************************************************************************/
friend class Window;
friend class View;

public:
    GUL_Scene(float l, float al, f_Direction d, void_Colour bg);
    void setLight(float l, float al, f_Direction d, void_Colour bg);
    ~GUL_Scene();

    virtual void add(GraphicObject * go);
    virtual void remove(GraphicObject * go);
};

#ifndef MOONLIGHT_OUTLINE
#include "GUL_Scene.icc"
#define INLINE inline
#endif

#endif
```

Figure A.17: GULScene.hh

```
//-*-c++-*-

#ifndef GUL_WINDOW_HH
#define GUL_WINDOW_HH

#include "Window.hh"

/************************************************************************/
class GUL_Window : public Window {
/************************************************************************/
friend class GraphicDevice;
protected:
    virtual void draw();
public:
    GUL_Window(char * n, void_Colour c, Screencoord t,
            Screencoord b,Screencoord l,Screencoord r);

    ~GUL_Window();
};

// no inline functions => no GUL_Window.icc
#ifndef MOONLIGHT_OUTLINE
//#include "GUL_Window.icc"
#define INLINE inline
#endif

#endif
```

Figure A.18: GULWindow.hh

Appendix B

ECOsim: class support for event-based programming

B.1 Introduction

This section describes the ECOsim class library and its usage. The structure of the section is as follows. Firstly, there is some background to the library and the motivation for writing it, then there is a high-level description of the libraries contents, behaviour and its interface, followed by a description of how to write Events and Entities, and lastly an illustration of the use of these, user-defined, Events and Entities in a simple application program.

The ECOsim library is being used in **`MOONLIGHT`** to provide interim support for event-based programming, during the development of the fully fledged ECOlib and system. In particular it is being used in the the development of the "BattleZone" application which accompanies the VOID libraries (see 4.7.3).

B.1.1 Motivation

The principle motivation for the development of the ECOsim class library has been to provide a minimal system to support the fundamental precepts of ECO, thus making it possible to develop programs in this paradigm in advance of the delivery of a full ECO implementation. It is designed to provide what is *necessary* rather than what we consider *sufficient*.

The main advantage to the system is that it encapsulates (a subset of) the functionality and interface of ECO and allows clients to use it without any knowledge of the underlying implementation. This is important because it will enable applications developed with ECOsim to be ported to the eventual ECO implementation with less work. The basic premise is that the effort involved in writing ECOsim and porting an application to ECO is less than the effort of re-structuring an application written in C++ to use ECO.

The system is minimal in several ways.

- it works only at the language level;
- it has minimal functionality;
- it is not optimised for performance.

The functionality will be covered in depth later in this document, for now it is enough to note that the ECOsim allows Entities to communicate with one another in a one-to-many manner using parameterised events with run-time type-checking.

The reason for working at the language level only is obvious: rapid development. Rapid development of the ECOsim was only feasible without the overhead of producing a run-time system and preprocessor (or compiler).

The system is unoptimised for performance firstly because it is only a prototype and secondly because, being implemented at the language level, it is precluded from performing some optimisations which would mandate preprocessing.

B.2 ECOsim: the user interfaces

Users of ECOsim can exist at two levels of expertise. Programmers can ignore the implementation details and simply use the ECO-style primitives of *subscribe* and *announce*, but they can only do this if they have Entities and Events defined for them to use. This gives rise to a second category of programmer, one who will define new, customised, Event and Entity types which can be used in applications. This latter type of programmer will naturally need to know a little more about the ECOsim implementation.

As a result, the ECOsim library really has two interfaces: that seen by the application programmer and that seen by the supporting programmer who designs the application specific Events and Entities. Note that neither of these programmers is required to understand all the internals of the implementation, but without preprocessing support it is a impossible to shield the support programmer from *all* the implementation details.

This relationship is illustrated in Figure B.1

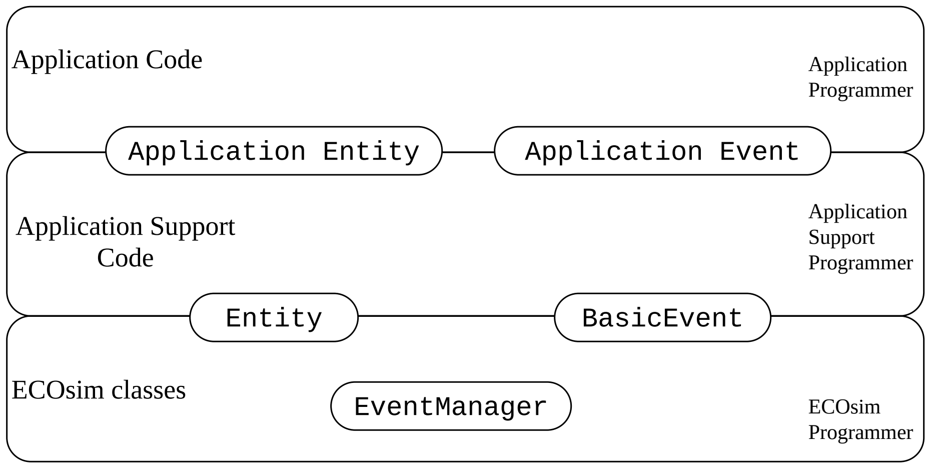


Figure B.1: Layers of encapsulation in ECOsim

B.2.1 Writing a program using events

The interface seen by the application programmer interface is very simple: some of the classes that they use will have been written by a support programmer[1], and these classes will have been derived from the library base class Entity. The use of this base-class gives the application programmer the interface shown in B.2.

Essentially, what the programmer is getting here is the cleanest possible language-based event communication primitives, *subscribe* and *announce*. Instead of these being primitives of a run-

[1]of course, the "two programmers" could be one and the same person

```
// ***************************************************************
class Entity {
// ***************************************************************
public:
    void subscribe(EventTypeID, void *);
    void subscribe(EventTypeName);
    void unsubscribe(EventTypeID);
    void unsubscribe(EventTypeName);
    void announce(BasicEvent &);
};

// ***************************************************************
// This macro is intended to take some of the hard-pointer arithmetic
// out of the subscription process
#define SUBSCRIBE(myclass,hname,event) \
{void (myclass::*hptr)(BasicEvent &) = myclass::hname; \
 subscribe(event, (void *) &hptr);}
// ***************************************************************
```

Figure B.2: Application programmer's view of Entity and derived classes

time, however they are part of the interface to all Entities. Additionally, the *SUBSCRIBE* macro hides the complexity of the subscription, which would otherwise reveal rather too much of the internal structure.

The application programmer client does not need to know anything about the mechanisms that allow an *announce* in one Entity instance to lead to event-handler's being called in zero or more other Entity instances. Also, the application programmer does not need to know anything about the BasicEvent class.

The application programmer *will* need to know how to construct the derived classes of Entity and BasicEvent that they intend to use. This can be best seen when we have examined the support programmer's role and the events and entities that they create.

B.2.2 Creating events and entities using ECOsim

The support programmer must derive (at least one) child class from the library Entity class. The author of the derived class should provide the functionality that is expected by the application programmer, as well as any initialising information for the constructor of the Entity class, which is deliberately inaccessible to non-derived classes.

This programmer should also derive at least one child class of the library class BasicEvent. This base class provides functions (only accessible by child classes) to manage an arbitrary number of parameters. It is part of the support programmers task to write a useful interface to these event parameters, the base class takes care of type checking and storage of these parameters[2].

The interface that the BasicEvent class presents to the support programmer is shown in Figure B.3 below.

Some requirements are placed upon the support programmer by the run-time typing system. All event classes must contain information about their type, which the will need in order to initialise the base class. The base class, in turn, needs this information for its dealings with the EventManager

[2]at present the parameters are limited to integer, floating point and string values, but this seems to be sufficient

```
// ***************************************************************
class BasicEvent {
// ***************************************************************
protected:
// get this value from the Event(Type)Manager iff this is the first
// instance of this event type in the program using the typeName
// else set it using the class static
    EventTypeID myType;

protected:
    BasicEvent(EventTypeName,EventTypeID &);
// NB ctor only available to derived classes

    void dieWithError(EvError);
    void addvStringParam(const vString &);
    void addFloatParam(float);
    void addIntParam(int);
    void setCurrent(int);                    // set the current element to the indexed val

    void getvStringParam(vString *&, int);           // will exit if type is incorrect
    void getFloatParam(float *&, int);               // will exit if type is incorrect
    void getIntParam(int *&, int);                   // will exit if type is incorrect

    void setvStringParam(const vString &, int);
    void setFloatParam(const float, int);
    void setIntParam(const int, int);

public:
    // note: public interface does NOT provide access to params stuff
    // any such access MUST be provided by the derived event class
    EventTypeID getType();
    char *className();
    Boolean typeCheck(EventTypeID);             // this will change to EventTypeName
};
```

Figure B.3: BasicEvent: the interface provided to derived classes

class[3]. Incorporating these restrictions the simplest possible decalaration and implementation of a new event type is shown in Figure B.4:

```
#include "BasicEvent.hh"

class Example : public BasicEvent {
    static EventTypeName classTypeName;
    static EventTypeID classTypeID;
public:
    Example();
};

Example::Example()
: BasicEvent(classTypeName, classTypeID)
{
    cout << "This is a new Example event\n";
}

EventTypeName Example::classTypeName = "Example";
EventTypeID Example::classTypeID = EVENT_TYPE_NOT_SET;
```

Figure B.4: A very simple derived class of BasicEvent

An equally simple Entity can then be derived to use this new type of Event, as shown in Figure B.5. This new Entity only has two methods: its constructor simply subscribes it to the Example event, naming its only other method (handleExampleEvent) as the handler for such events.

The Receiver Entity shown in Figure B.5 is, as its name suggests only receiving Events. We can write a complimentary class Sender which will announce events, as shown in Figure B.6. It should be noted that this division is quite artificial, and that there is nothing to prevent ECOsim entities from both announcing and handling (multiple) events.

B.2.3 Writing programs which use entities and events

With the creation of such simple derived classes the application programmer can write a very simple program to use these classes, as shown in Figure B.7.

NB: the event that is sent and received in this example goes to only one entity instance, but if we add several instances of Receiver, then the event is delivered to each one.

More complicated examples are provided in the distribution, in particular examples showing the use of the parameter manipulation facilities and examples showing the use of run-time typing to distinguish which of several possible events has been delivered to an event handler.

B.3 Design and Software Architecture of ECOsim

The public interfaces that have been shown in the preceding section are of course greatly simpler than the actual implementation of ECOsim. The internal structure of the library classes incorporates the following classes:

[3]the EventManager class is completely hidden from both sorts of client programmer

```
#include "Entity.hh"

class Receiver : public Entity {
public:
    Receiver();

    void handleExampleEvent(BasicEvent &);

};

Receiver::Receiver()
{
    SUBSCRIBE(Receiver,handleExampleEvent,"Example");
}

void Receiver::handleExampleEvent(BasicEvent &ev)
{
    cout << "Receiving an event of type " << ev.className() << "\n";
}
```

Figure B.5: Derived type of Entity, with one event-handler

```
class Conductor : public Entity {
public:
    Conductor();

    void method();
};

Conductor::Conductor()
{
}

void Conductor::method()
{
    Example myExample;
    announce(myExample);
}
```

Figure B.6: Second derived type of Entity, which announces events

```
int main()
{
    Receiver myR;

    Sender myS;

    myS.method();
}
```

Figure B.7: The "Hello World" of event programs

- EventManager
- BasicEvent
- Entity
- EventDataItem
- EventNameIDMapping
- EventSubscriberList

The relationship of these classes is captured in Figure B.8, which uses Booch notation to show the inheritance and usage relationships of these classes.

B.3.1 ECOsim Implementation

In the following text we describe the basic function of each of these classes:

EventManager The EventManager class is entirely hidden from the user, through the use of C++ static functions which enable calls to be made to the EventManager *class* without requiring that any EventManager instance has already been created. This programming hook allows an EventManager to be created when it is needed at run-time without involving the client code.

The EventManager contains two important data-structures: the Event Type Register, which maps event names to IDs; and the list of SubscriberLists. This latter is central to the system, there is one EventSubscriberList for each registered event in the system. Each instance holds a list of pointers to Entities, and each of these Entities is subscribed to that event.

BasicEvent The BasicEvent provides typed parameter management for its sub-types, and also interacts with the EventManager to maintain the run-time typing system. When an instance of a BasicEvent is created it checks its class static member `classTypeID` and if this has not been initialized then this instance is the first instance of that event type to have been created in the program. It therefore proceeds to call the EventManager class static method `registerEventType`[4], to inform the EventManager that there is a new type of event in the system, passing it the (text) name of the class and receiving in return a unique type-identifier.

[4] as described above this is also a hook to trigger the creation of an EventManager if none already exists

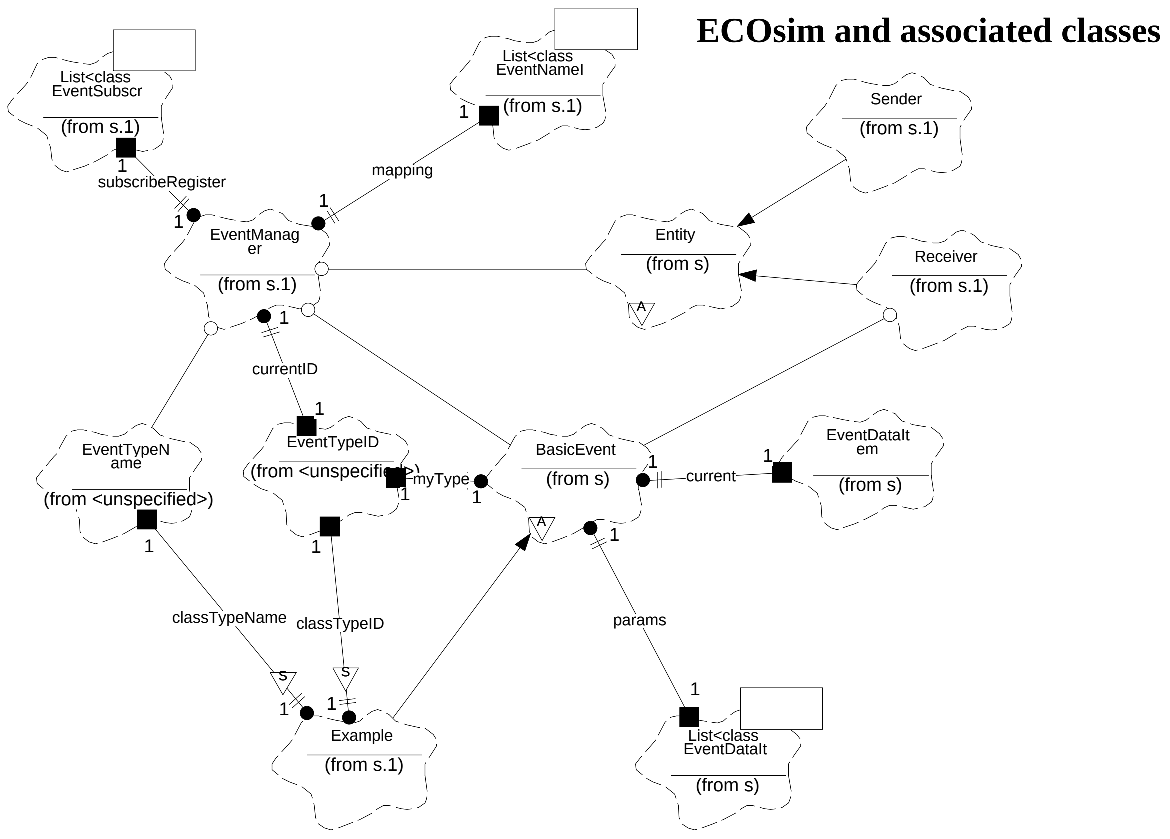


Figure B.8: Booch notation for the ECOsim lib and simple example

Entity The Entity base class provides two important functions: firstly, it provides the API for subscription and announcement of events, and secondly it encapsulates all interaction between the application and the EventManager.

As with BasicEvent, the first instance of an Entity must register with the EventManager[5], but in this case it is not for typing reasons, but simply to establish to which EventManager it is talking.

The subscription process has two parts. (telling the EventManager, storing the upcall pointer) (handler invocation), (changing the subscribed method.

EventDataItem This simple class is used to maintain a mapping between a BasicEvent parameter and its type.

EventNameIDMapping This is a simple class to maintain a mapping between an event type name and its ID.

EventSubscriberList As mentioned above there is one EventSubscriberList for each registered event in the system. Each instance holds a list of pointers to Entities, and each of these Entities is subscribed to that event. When an event of a given type is announced all the entities on the appropriate list are given the event.

B.4 Future work

Despite its intended role as a short-term solution ECOsim has been written to be distributable (for example, the parameter list management of `BasicEvent` is directly applicable to marshalling for remote RPC communications), and is open to multi-threaded extension.

Any distributed version of ECOsim would probably use a derived class of `EventManager`, which communicates with other EventManagers in other applications and on other machines. It would also be feasible to derive sub-classes of `BasicEvent`, `LocalEvent` and *GlobalEvent* and to provide explicit support in the EventManager for scoping using these classes.

To make ECOsim multi-threaded would involve insertion of some synchronisation code into the base classes (in this case `EventManager` and `Entity`. Again, inheritance could be used here to allow choice among several synchronisation policies for any given application specific Entities.

[5]As before, it must cause the creation of one if none has been created yet.

Appendix C

The ECO model: events + constraints + objects

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Abstract

This document describes the rationale and design of a programming model based on events, constraints, and objects and the use of this model in the Moonlight[1] project. It describes the inter-object communication or invocation mechanism, and the way in which concurrency, synchronisation, and timing properties are expressed and controlled. The invocation mechanism is unusual in that it is *event-based.* It encourages loose coupling among the objects and this supports a high degree of encapsulation for each object. Concurrency, synchronisation, and timing properties are expressed in a uniform way using *constraints* which may be associated with objects and events. We describe the way in which the abstractions of the ECO model are expressed at the language level, and the support for them which is required from the runtime code and the underlying system.

C.1 Introduction

Large parallel and distributed applications are hard to program. Communication, synchronisation, and timing contribute to the complexity of this task. Object-orientation is advertised as a good paradigm for the modelling of entities in the application domain and a programming model which allows more structured and less complex program development. The Moonlight project is building an object-oriented environment for developing and executing games and virtual world applications. Some of the requirements coming from such an environment are:

- support different patterns of communication. As an example, a single object may collect information from a number of sources or disseminate information to a number of destinations. In general, there may be exchange of information between groups of objects, and the group membership may change dynamically.
- support soft real-time applications. It must be possible to express timing constraints on object behaviour. Such constraints arise out of the application domain and the way in which audio and video data are handled. When the constraints are occasionally not satisfied there are no catastrophic consequences for the system or for its environment.

[1]This work is partially funded by the CEC under ESPRIT contract No. 8636

- support distributed and persistent applications. An application may span a number of nodes in which case its objects communicate over a network. In some cases the objects will have to be persistent, i.e., retain their state across separate executions.
- support large applications with thousands of objects, where new objects may be created and the existing ones may disappear dynamically. This brings out the importance of issues like scalability and scoping rules.

This document describes the rationale and design of the ECO programming model and its use in the Moonlight project[2]. It includes the inter-object communication or invocation mechanism, and the way in which concurrency, synchronisation, and timing properties are expressed and controlled. A number of other important issues, like persistence, grouping, and mobility of objects are not considered in this document. The invocation mechanism is unusual in that it is *event-based.* It encourages loose coupling among the objects which supports a high degree of encapsulation for each object. Concurrency, synchronisation, and timing properties are expressed in a uniform way using *constraints* which may be associated with objects and events. We describe the way in which the abstractions of the ECO model are expressed at the language level, and the support for them which is required from the runtime code and the underlying system.

The next section gives more details about objects with events and constraints and their possible implementation. Section 3 gives several examples and section 4 surveys some related work and compares it with the work reported in this document. The last section summarizes the main ideas, describes the state of the present implementation and sets out future work.

C.2 Objects, events, and constraints

The basic abstractions of the ECO model are objects, classes, events, and constraints. In this section we first briefly describe those properties of objects and classes which are relevant for the description of events and constraints.

Objects communicate by announcing events and by processing those events which have been announced. Each object is an instance of a class, it has instance variables and a number of methods which operate on these variables. A class specifies the interface to its instances (signatures of the methods which may be invoked on the instances), together with the events and constraints used by the instances. A method can be bound to one or more events in which case it behaves as an event handler. It is invoked when the event is announced, and it can itself announce one or more events. Several methods of an object can be bound to the same event. The type of an event determines the number and types of its parameters. In order to bind a method to an event the method signature has to match the event signature. The objects which announce an event are the *sources* of the event. Each occurrence of an event can affect zero or more objects (can be delivered to them causing invocations of their methods) — they are the *destinations* of the event. A source announces events without having to worry about the identities or locations of the destinations. Similarly, a destination object registers its interest in an event without having to worry about the objects which may announce the event. If necessary, both naming and location information can be expressed using event parameters.

Binding between a method and an event is dynamic. The method can stay bound to the event from the moment its object is created until the object is deleted. Alternatively, the method is bound at some arbitrary moment during the object lifetime and the binding can be changed after that. In our present design events have global scope, and sources and destinations may be located at different nodes of the distributed system. We intend to introduce some form of scoping at a

[2] An earlier description of the same can be found in [13], which also describes other work on the Moonlight project done by the Distributed Systems Group at Trinity College Dublin. For more information on this project and work of all the partners involved contact moonlight@dsg.cs.tcd.ie.

later stage (possibly using the idea of spatial and temporal localities and area of interest managers described in [40]).

A constraint specifies a condition that should be either monitored-only or maintained and monitored. It is defined over some domain, in our case the domain includes event parameters, object instance variables, and possibly some constraint specific data. Constraints are evaluated at the observable points (the start and end of an event handler). The scope of a constraint is its enclosing class. There are different kinds of constraints, categorized by the data which they can access, by their evaluation points, and by the actions which they are allowed to perform. The information used by the constraints depends on the application. There may be a library of pre-defined constraints (e.g., those which implement typical synchronisation or timing constraints).

A program is a collection of cooperating objects, possibly placed on multiple nodes. When it is started, one of its objects must subscribe to the special *start* event announced by the system (a number of objects may subscribe to this event, i.e., there is not necessarily a single entry point per program). An ECO implementation[3] may automatically, or when instructed by the user, add a handler for this event to one or more objects and allow the user to override this default handler. The same can be done in some other cases, e.g., default handlers for special debugging events may optionally be added to objects. Once the program is started the objects communicate with each other by announcing events and by being notified of event occurrences. They can also express their interest, or lack of interest in specific events. The program may decide to end when it learns about an occurrence of some event.

The ECO programming model can be made available in different existing languages. Two ways in which this can be done are ([7]):

- extend an existing language by making the new abstractions visible or explicit, or
- add support for the new abstractions using the existing language mechanisms (e.g., by inheriting from library classes which support the new abstractions).

Which approach is chosen depends on a specific language and the required extensions. The second approach may be easier to implement and easier to use (the original language remains unchanged). However, if the extensions are of a fundamental nature (e.g., a new inter-object communication mechanism, or a new form of inheritance), it may be difficult or impossible to integrate them seamlessly into an existing language. The first approach changes the language, with all the consequences which this brings (lack of compatibility with the old language, the extensions may not agree with the style of the original language). However, a language processor used by the first approach provides more flexibility, especially in the mentioned cases for which the second approach is less suited. In this section we show a way in which C++ [54] is extended with events and constraints.

C.2.1 Declaring events

Events have global scope and constraints have class scope. An event is defined with:

event EventName(parameters);

EventName is globally unique, and *parameters* is a list of event parameters (their names and types). A class declares its *in-events* and *out-events* with:

outevents list of EventNames;

inevents list of EventNames;

The former are those events which the instances of the class may announce, and the latter are those which they may handle. In a way, they are similar to the *import* and *export* statements in Modula-2 [61]. However, *in-events* and *out-events* differ from these statements. *in-events* lists those events in which the instances of the class may express interest at some moment during their lifetime. *out-events* lists those events which the instances may announce to their environment.

[3]A compiler or language preprocessor.

C.2.2 Notify constraints

Constraints are named conditions which use some data and which control the propagation and handling of events. A *Notify* constraint is optionally provided by a destination object when it subscribes to an event. The only data which can be used by this constraint are the values of event parameters, and the identity of the source[4] (plus optionally some constants). The destination object uses a Notify constraint to express: *I want to be informed about those occurrences of the event which satisfy this condition.* Since a Notify constraint does not depend on the local state of the destination object it can be evaluated in the context of a source object, or some *event manager* object. An example of a Notify constraint is given next.

> **constraint** CountLevel { $(count = 1), (count + level < 2)$ }
>
> CountLevel is the constraint's name, *count* and *level* are the names of two parameters[5]. of the event which is associated with this Notify constraint. The constraint requires that the value of the event parameter *count* is equal to 1, and that the sum of values of the event parameters *count* and *level* is less than 2.

A Notify constraint is associated with an event at subscribe time (when the destination object subscribes to the event). A group of objects may have mutual agreement that for example the first parameter of an event is the address of the intended destination object, or that it is the latest time when handling of a particular event occurrence should start, or that it is the priority of an event occurrence. Each of the destinations can use a different Notify constraint to specify when an occurrence of this event type qualifies to be delivered. This can be used to specify for example: *deliver to me those occurrences which are sent to me directly*, *deliver to me those occurrences which are sent with a sufficient maximum delivery delay*, or *deliver to me those occurrences which are sent with sufficiently high priority.* In a video game for example, a *collision manager* object may be used to detect collisions among game objects. It announces the *collision* event with the identities of the colliding objects passed as the event parameters. The interested objects may use Notify constraints as filters; only those collision notifications which are of interest to a specific object will be delivered to the object.

C.2.3 Pre and Post constraints

The *Pre* and *Post* constraints are used by a destination object as method wrappers. They use the object instance variables plus optionally constraint internal data, and may be used to implement:

- synchronisation within the object (e.g., Pre and Post constraints may be used to implement synchronisation variables from [20], these variables would be constraint internal data),
- control of the concurrency level within a method or within the object,
- timing control (e.g., earliest and latest method start-time and end-time, method duration from [3], and [36]),
- method pre- and post-conditions, method and object invariants — used for the runtime verification of object consistency and application correctness.

In addition to accessing and possibly modifying the instance variables and constraint data, Pre and Post constraints can announce an event, and Pre constraints can request that the current notification is: *discarded*, *enqueued*, or *processed.* This allows constraints to have *wait* or *failure* semantics [36]. In the case of *failure* semantics a constraint is used only to monitor a certain

[4]It is assumed that each object has a unique identifier.

[5]*source* is used in a Notify constraint for the identity of the source object

condition (e.g., the values of some instance variables). When a notification arrives and the precondition is not satisfied the constraint requests that the notification be discarded, optionally some event may be announced which will inform others about this failure. In the case of *wait* semantics when a notification arrives and it is found that the condition is not satisfied the Pre constraint may enqueue the notification for later processing[6]. Conceptually, each Pre constraint may have associated with it a queue of notifications. In order to allow the queued notification to be processed, a Pre or Post constraint may request *dequeuing* of a notification from one of the queues associated with the object's Pre constraints. When a notification is dequeued its Pre constraint will re-evaluate it, which may result in the notification being discarded, processed, or enqueued again. An example which shows how this works is given next.

> A ResourceManager object manages some number of resources, and has one of its methods bound to the GetResource event and one of its methods bound to the FreeResource event (these events are announced by other objects). A Pre constraint for the method bound to GetResource can check if there are any available resources. If are none it requests that the current event notification is *enqueued.* A Post constraint for the method bound to FreeResource requests that a notification is *dequeued* from the queue associated with the Pre constraint of the GetResource (if the queue is empty *dequeue* does nothing).

A Pre constraint may also request that a notification is *processed.* This is done when it is found that the condition is satisfied and that the object can proceed with handling the notification. There are two options: *process-active* and *process-passive* which can be used to control the level of concurrency within an object. If *process-passive* is requested there is a procedure call to the event handler (the event parameters are passed to the handler, which may require that they are unmarhsalled first if the notification is received from a remote source). If *process-active* is requested a new thread is created to execute the event handler (the event parameters are again passed to the handler). Each of the *discard*, *enqueue*, *process-passive* and *process-active*) statements ends the processing of the corresponding Pre constraint. Announcing an event and dequeuing notifications does not end the current constraint.

The *discard/enqueue/dequeue/process* options available to the constraints place the responsibility for implementing the synchronisation, timing, and other policies on the user. This mechanism has some potential disadvantages:

- it may be regarded as too low-level. However, this may not be a problem since we expect that there will be sets of frequently used constraints available to applications (e.g., constraints which implement one-writer/multiple-readers access policy, or which implement some typical timing constraints).

- The queueing of notifications may be too restrictive in some cases. There is a single queue per method, and the *enqueue* and *dequeue* allow appending to the end of the queue and removing from the front of the queue. Other possibilities (e.g., priority queues, various kinds of searching through the queue) may be required by some constraints. However, the described constraint options are intentionally left simple as it is expected that they will be sufficient for a number of applications[7]. In other cases, constraints may be implemented by specialised objects.

C.2.4 Announcing events and subscribing to events

An event is announced with:

[6]This will be done when it is believed that the same notification may satisfy the condition at some later time, which may be the case for instance with synchronisation and timing constraints.

[7]If required, it would be easy to increase the expressive power of constraints with extensions like: allow specification of *priority* with *enqueue* and *process-active*; or allow *flushing* of a queue.

announce EventName(parameters)
The *EventName* must be on the *out-event* list of the object's class. The announcement is asynchronous, the announcer does not wait for some "reply event" or for some object to handle the event. A method can be bound to an event initially (when the object is created), and can change its binding dynamically. The former is done in the class definition with:
MethodName(parameters) **handles** (EventName, NotifyName, PreName, PostName);
and the latter is done within the code with the *subscribe* and *unsubscribe* statements:

```
subscribe MethodName (EventName, NotifyName, PreName, PostName);

unsubscribe MethodName EventName;
```

in both cases the names of the constraints are optional. *MethodName* is local to the object which invokes *subscribe/unsubscribe*, and *unsubscribe* flushes the queue of the method/event Pre constraint. It is expected that *subscribe* and *unsubscribe* will be used to express object's current interest in certain events, while a Notify constraint will refine the specification of an object's interest in a specific event. It is possible to subscribe to or unsubscribe from a number of events. The following shows an example of a class with events and constraints:

```
event E1(···);
event E2(···);
event E3(···);
class myclass {
   inevents E1, E2;
   outevents E3;
   notify_constraints
        N { ··· }; // Notify constraint
   pre_constraints
        C1 { ··· }; // Pre constraint
   post_constraints
        C2 { ··· }; // Post constraint
   methods
        mymethod(···) handles (E1,N,C1,C2);
}

myclass::mymethod(···) {
        announce E3(···);
        unsubscribe mymethod E1;
        subscribe mymethod (E2,,,);
}
```

In this example, the method first subscribes to E1 with some constraints, and then (after announcing E3) it unsubscribes from E1, and subscribes to E2 without any constraints.

C.2.5 Implementation

This subsection describes a way in which some of the above concepts may be implemented, other implementations are possible.

Whenever an event definition is found in the code the event descriptor is registered in the Event Register (event descriptors are persistent and shared by the applications). Each of the events which appears on the *in-events* and *out-events* lists of a class must exist in the Event Register. In addition to this, for each event the code for marshalling and unmarshalling of its parameters has to be generated. At runtime, whenever an event is announced the information related to this event occurrence is used to evaluate the Notify constraints associated with the event. Event notifications are passed to the destinations of the satisfied Notify constraints. At the destination side, Pre and Post constraints are associated with methods, and support for *discard*, *enqueue*, *dequeue*, *process-active*, and *process-passive* is provided.

For the Notify constraints, there is code which will encode them and forward each of these constraints to all the sources of a specific event. At the source side, there is code which maintains the Notify constraints. The constraints are evaluated whenever their events are announced. An *event manager* object (EM) may be implemented per object/per event, per object (for all its events), per group of objects, or per node of the distributed system. One of the EM tasks can be maintaining and evaluating all the Notify constraints of the object's *out-events*. All the objects which can announce the same event can be registered as a group. If the underlying system supports group communication it can be used to inform all the sources about changes in the bindings (a new Notify constraint added, or an existing Notify constraint removed). When an object is created, or when an existing object is brought into memory, it joins all the groups of its *out-events*. When an object is deleted, or moved out of memory, it leaves all the groups of its *out-events*.

Groups of event sources allow easier distribution of information about Notify constraints. In a distributed system it may be desirable to evaluate the Notify constraints as near the sources as possible, since this will stop the network traffic of unwanted notifications. An alternative to the groups of sources would be to use groups of destinations. This would make the distribution of notifications easier, but the possible price is distributing a lot of unwanted notifications if the Notify constraints are evaluated at the destination side. A third scenario which would have both: (a) groups of sources and Notify constraints evaluated at the source side and (b) groups of destinations, leaves open the question: "what criterion should be used to group the destinations". The conditions under which a notification is discarded by a Pre constraint application specific and with multiple such constraints it seems less likely that they can be used to form groups of destinations.

The use of the group communication mechanism described here is new. The usual way is to have groups of processes or threads, in our case there are groups of objects (it may be groups of EM objects). The only other reference that has groups of objects we know of is [31]. Also, groups are usually used for fault-tolerance, but as stated in [31] they can be used "as an addressing construct to accurately track a set of processes that share some characteristic". In our case we track sets of objects and the shared characteristic of the objects in a group is their ability to announce the same event. The group mechanism should be lightweight in order to cope with a large number of potentially overlapping groups [60]. The underlying system has to support lightweight threads and asynchronous communication (messages are used to communicate event occurrences to remote nodes). The basic requirement, with respect to the reliability and ordering properties of the underlying communication is: no guaranteed delivery and no guaranteed order. Some applications may require more, e.g., a causal or total order of the event announcements, subscribes, and unsubscribes.

C.3 Examples

It was already stated that events allow loose coupling between objects. An object may announce events for different reasons, some examples are:

- announce "x happened locally" (where x means a specific local action was performed or a specific local state was reached),
- announce "x happened locally, this will interest X", where X may be the name of some object or a group of objects. In this case the announcer knows the names of destinations,
- announce "I need y done by someone" (by anyone who can do it),
- announce "I need y done by Y" (where Y is the name of some object or a group of objects).

The first and third cases are anonymous communications, and second and fourth cases are named communications. With the event-based communication mechanism the names of destinations may be passed as event parameters, i.e., events support both anonymous and named communication.

The rest of this section shows different ways in which constraints can be used. The first example is of the previously described ResourceManager (slightly extended, the pool of managed resources may be *empty* or *full*). If a request for resource was announced and the pool is empty the request is queued; if a resource return was announced and the pool is full the return request is queued. In this example we assume that there is no need to control the level of concurrency within the object. The next example will show how this can be done. Also, the examples are sufficiently simple so that there is no need to use Notify constraints. Only the code related to constraints is shown.

```
class ResourceManager {
    pre_constraints
        PreGive { if (isempty) enqueue else process-passive; }
        PreRet { if (isfull) enqueue else process-passive; }
    post_constraints
        PostGive { if (wasfull) dequeue(PreRet); }
        PostRet { if (wasempty) dequeue(PreGive); }
    methods
        GiveResource(···) handles (GetResource,,PreGive,PostGive);
        ResourceReturned(···) handles (FreeResource,,PreRet,PostRet);
}
```

isfull, *isempty*, *wasfull*, and *wasempty* are boolean expressions which depend on the local state of the pool. The second example is of a consistent buffer. It manages some data and allows either multiple active *reads* or a single active *write* within the object:

```
class ConsistentBuffer {
    pre_constraints
        PreRead {
                if (current_write == 0) {
                        current_read++;
                process-active }
            else enqueue; }
        PreWrite {
            if((current_read == 0) && (current_write == 0)) {
                current_write++;
                process-active }
            else enqueue; }
    post_constraints
        PostRead {
            current_read- -;
            if(current_read == 0) dequeue(PreWrite); }
        PostWrite {
            current_write- -;
            dequeue(PreWrite);
            dequeue(PreRead); }
    methods
        Read(···) handles (ReadReq,,PreRead,PostRead);
        Write(···) handles (WriteReq,,PreWrite,PostWrite);
}
```

Dequeuing of a notification can be seen as causing an "internal object event". The code which evaluates the object's constraints is sequential, and such "internal events" are processed before processing of any external events is done. The level of concurrency is controlled at the observation points, it is not possible for a constraint or method to suspend or abort a method of the same object. Next, we describe the way in which some typical timing constraints can be implemented.

1. *start after time* and *start before time* requirements are implemented as Pre constraint. The *time* may be received as an event parameter or specified by the destination object. It may be required to enqueue a notification for later evaluation. In this case a timer event can be used to trigger dequeuing of such notifications and re-evaluation of the Pre constraints.

2. *finish after time* and *finish before time* requirements are implemented as either Pre or Post constraints. The *time* may again be received from the event announcer or specified locally. If the constraint is found to be unsatisfied an event may be announced which will cause error processing and possibly some recovery.

3. *maximum duration time* and *minimum duration time* are implemented with both Pre and Post constraints. Otherwise, they are similar to the above timing constraints.

In addition to synchronisation, concurrency, and timing, constraints can be used to express method pre-conditions, post-conditions, and invariants. Some of the ways in which they appear in other languages are given next (p is a boolean expression over the object state):

- *always p* or *invariant p*,
- *required p* or *when p*,
- *ensures p*.

The first case is a method invariant and it is implemented with both Pre and Post constraints. A method pre-condition (the second case) is implemented as a Pre constraint, and method post-condition (the last case) as a Post constraint. In these examples, if a Pre constraint is not satisfied the event notification is usually discarded (optionally some event may be announced). If a Post constraint is not satisfied it is usually accompanied by announcing some event.

C.4 Related work

A possibility of an event-based general-purpose communication mechanism has been suggested in [45]. This ought to be seen in the context of other proposals for language and system support for communication (where the communicating entities can be processes, threads, modules, or objects).

An early comparison of message passing and shared memory (or procedure-based) mechanisms is reported in [38] and [50]. Some of the more recent related work can be found in [1], [9], [22], and [60]. The remote procedure call (RPC) was introduced as a convenient extension of the procedure call [47]. Its basic form is synchronous, two-way, and one-to-one exchange of messages ([11], [18]). It encourages the client-server view of the world and influences the way in which programs are designed and implemented. The need for one-to-many, many-to-one, asynchronous, one-way, and other forms of communication has led to the extensions of the basic RPC ([8], [24], [59], [62]), and to completely different approaches (e.g., [12], [14], [16], [21]).

An event based language for parallel programming called EBL is described by Reuveni [49]. In this language events are the only control mechanism and cause the activation of event handlers. Event occurrences can be permanent or temporary and events can be recurrent or non-recurrent. Recurrent events can have multiple active occurrences, independently of whether they affect one or more destinations, and non-recurrent events can have only one active occurrence at any time (occurrences overwrite each other and only the last one survives).

The basic computational step is the announcement of an internal event (an event caused by the program, external events are caused by hardware). EBL is not object-oriented, instead a program consists of a collection of modules and each module consists of a number of event handlers. Events are typed; each event type has a name. All the occurrences of the same type of event have the same number and type of parameters (a parameter can be of an event type, in addition to simple types). The only action possible in an event handler is the announcement of one or more events. Several events can be announced sequentially or in parallel. A handler can be augmented with a condition which has to be satisfied before the handler is invoked. Reuveni also discusses the importance of scoping of events, the ways of achieving synchronisation with events, and the expressiveness of event based languages. Our work has been influenced by [49] and can be seen as an attempt to use some of these ideas in an environment which has objects and constraints.

The *generative communication* promoted by Linda [14] allows processes to communicate via the *tuple space*. A sender inserts a tuple (a list of typed data fields) into the space without having to worry about the identity and locality of the receivers. Receivers can inspect or remove tuples from this space by specifying a template tuple. The reception occurs when a match for the template tuple is found. Communication through tuple space is used in [42] in the context of distributed object-oriented languages. Oki et al. [48] use a variant of the Linda approach, called *anonymous communication*, where one field of each tuple is the subject field, and reception is based on the matching of the subject fields. Similar to the original approach, communication is independent of the identities and locations of senders and receivers. Agha and Callsen [2] describe Actorspace, a programming paradigm which integrates Actors [1] and Linda style communication. Actor-names can be expressions, they are evaluated in order to find the actors whose names satisfy the given expression. Actorspaces provide a scoping mechanism, are named and can form a hierarchy. The control of the names visibility, as well as control of the scope lifetime, is explicit and dynamic. Our approach has similar goals, but it is based on parameterized events and Notify constraints.

It is often stated that distributed systems require group communication, where the group membership changes and is determined by the global state of the computation (e.g., [2], [9]). Our work is in line with the attempts to support multiple and changing communication patterns. The loose coupling of objects avoids "the tendency of distributed naming systems to resolve names before communication occurs" (Bayerdorffer [9]), and our constraint mechanism allows communications to be specified in terms of local object states. The *associative broadcast* primitive of [9] allows the sender to provide an expression over attributes with each outgoing message. These expressions are evaluated locally where the potential receivers reside and depending on the outcome of this evaluation the messages are or are not delivered. Bayerdorffer considers events associated with naming and communication. Our events can be associated with naming and communication, but they can also be external events, timer events, and scheduling events [52].

Menon et al. [45] have thread-based and object-based event handlers. In ECO there are only object-based handlers. They also mention several applications for which events are especially suitable: distributed monitoring, debugging, and exception handling. The idea of loose coupling among communicating entities (this time to ease the integration of software components) is also used in [27] and [55]. There is insufficient space here to compare various other ways in which events are used (e.g., [23], [30], [37], [41], [51]).

Communication and control flow are often closely related — for instance communication primitives can be blocking or non-blocking. Depending on where and under what conditions this blocking is done it is possible to classify various primitives and languages with respect to their support for concurrency and synchronisation control [6]. There has been much work on language support for controlling the level of concurrency within objects and the order in which events occur. Arjomandi et al. [7] overview various approaches to adding concurrency support to a programming language. We use constraints to specify the level of concurrency within an object and do not make threads visible (except through *process-active* and *process-passive*). Some of the work on synchronisation constraints is reported in [10], [26], [43], and [58]. Frolund [26] have constraints specified as part of a class definition and each constraint restricts the set of methods which may be invoked when an incoming request is received. A constraint may depend on the parameters of the received invocation and the state of the target object[8]. Both [26] and [58] allow composition of constraints. The former is concerned more with the permissive and the latter with the restrictive aspect of constraints. In [26] each object has a controller which evaluates the constraints and may delay invocations (event deliveries) if there is a chance that this will make them acceptable in future.

The Archie language [10] allows specification of synchronisation states (or method pre-states), and method post-states, and integrates these states with type information. It also addresses the problem of multi-party synchronisation by introducing multioperations and coordinated calls based on [8]. In our case, the constraint mechanism can be used to express the required order of event announcements and deliveries at the level of a single object. Multiparty synchronisation may require complex expressions involving multiple events which we do not support at present. Our constraints allow the implementation of *activation conditions* [20], which are based on *synchronisation counters* [5]. An activation condition is attached to a method, and can depend on the instance variables, names of the methods, invocation parameters, and synchronisation counters. The counters are the object instance data maintained by the system and showing for instance the number of times each method was started, finished, or started and not finished.

The timing behaviour of a system is naturally described with constraints on event occurrences ([4], [19], [34]). Language support for expressing these constraints helps the development of programs which meet their timing specification [29]. Kenny and Lin [36] state that for a real-time system "there must be a way to define the constraints on time and resources to the computations. Some notion of a *constraint* must therefore be part of the system". Their language (Flex) has a constraint mechanism as a basic programming primitive. Flex constraints are associated with blocks of code. Exception handlers may be provided and will be executed when some of the constraints fail. An important concept used by various real-time languages is that of *observable points* [29].

[8]Frolund mentions the possibility of using "history instance variables" in the constraints.

They can be seen as markers, relevant for evaluating constraints, for making scheduling decisions and for tuning the code. Different languages have different notions of observable points. In our case, the observable points are at the object level (start and end of an event handler); in Flex they are at the level of a block of code.

The authors of [3] and [33] describe different ways of expressing timing constraints and integrating them into an object-oriented language. Timing behaviour can be described by specifying the minimum and maximum time when a certain observation point in the code is reached, or by specifying the time interval between two observation points. RTC++ [33] allows timing constraints both at the operation and statement level. It also allows a non-timing constraint to be specified for an operation, which can depend on the instance variables and message parameters. A function may be provided which is invoked when a constraint is not satisfied, and which will decide whether or not the invocation should be queued. The approach described in [3] relies on real-time *composition filters* for expressing timing constraints. There are input and output filters, specified at the class level. When an invocation message is received it is matched against the input filters for the class. The matching consists of evaluating a named expression which can depend on both instance and external variables. The method names can also be used for matching — a filter can be shared by several methods of an object. When a match is found the timing constraint from the corresponding filter is used. Our approach is similar but simpler (it has fewer basic abstractions) and more general.

Events and constraints have been used for constructing *active databases* with their Event-Condition-Action programming model (e.g., [15], [28]). Gehani et al. [28] support events and *triggers* in a database programming language. The events are of interest to one object or of interest to a group of objects and can be:

- *basic events* There is a number of predefined basic events, e.g., creation or deletion of an object, invocation of a member function, time-related and transaction-related events. A member function (its signature) can be used as a part of an event declaration.
- *logical events* They are the basic events optionally associated with *masks*. A mask is a predicate which specifies which occurrences of an event are of interest. It can use the parameters of the event being masked, or it can use the state of an object.
- *composite events, logical composite events* A composite event combines several logical events using the logical operators (and, or, not) and special event operators. The latter allow among other things specification of event order and periodic events.

The work reported in [28] is similar to our work in some ways. One important difference is that in our case events are used as a general communication mechanism. Also, we do not have composite events, but they can be supported at a higher level. A mask is similar to our constraint, but the latter cannot depend on the state of arbitrary objects. In [28] events are local to an object, and *triggers* are associated with a class definition. A trigger links an event with an action, and is active either perpetually or until the associated event is observed and the action is fired. The trigger corresponds to our facility to subscribe/unsubscribe to an event (both serve to link an event, constraint, and action). In [28] an action can be an arbitrary statement block while in our case an action is an event handler which is a method of some object.

In addition to being used for concurrency, synchronisation, and timing, constraints are used for specifying object invariants ([46]), and as a general construct in declarative languages (e.g., [25]).

C.5 Conclusions, present state and future work

This document describes the ECO programming model and its use in the Moonlight project. The event-based mechanism is used for communication among objects, it allows a higher degree of encapsulation and simplifies development of large and complex applications. A generalised constraint mechanism allows specification of a number of different requirements (synchronisation and concurrency within an object, timing behaviour of an object, and object's invariants). Although events and constraints have been used elsewhere, this combination of events, constraints, and objects allows a new and often more natural style of programming. Since events diminish the importance of object references they may allow new approaches to persistence and garbage collection.

At present, we are implementing the support for the ECO model in a single address space, which is the first requirement in the Moonlight project. In addition, the project aims at providing a set of tools which will help the user to create new games and virtual world applications. In such an environment, as already mentioned, there are a number of additional issues which will have to be resolved. One of them is scoping of events. Another is the required kind of inheritance. It is known that inheritance may interfere with synchronisation and timing constraints ([43], [26], [3]). In our case, constraints allow separation of the synchronisation and timing code from the "ordinary" application code. A library of typical constraints may be provided. It remains to be determined whether, in such an environment, there is a need for inheriting constraints and if there is then how it should be done. More important than this is to provide some support for expressing complex constraints which involve multiple events and multiple objects[9]. It may be possible to do this at a higher level using the basic building blocks described here.

Acknowledgements

The following people contributed with their comments and in other ways to the work reported here: A. Condon, A. Donnelly, N. Harris, S. McGerty, C. McHale, K. O'Connell, P. Taylor (Trinity College Dublin), D. Belsnes, B. Hauksson, A. Lie (Norsk Regnesentral Oslo), P. Caselles, L. del Pino (APD S.A. Madrid).

[9]A simple example of this is synchronous communication which involves ordered *request* and *reply* events, and may involve two or more objects.

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