Proceedings of the 1986 Winter Simulation Conference
J. Wilson, J. Henriksen, S. Roberts (eds.)

SIMULATION MODELING IN AN OBJECT-ORIENTED ENVIRONMENT USING Smalltalk-80

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ABSTRACT

Object-oriented environment of Smalltalk-80 is investigated as a potential tool for simulation modeling. Basic features of the Smalltalk-80 language are described including messages, objects, classes, and inheritance. A simulation control framework for Smalltalk-80 is explained using a simple example. Smalltalk-80 language appears to have a number of features that makes it unique when compared to traditional simulation languages. A comparison of Smalltalk-80 with the traditional simulation software concludes the paper.

1. INTRODUCTION

In the last few years, the object-oriented paradigm of computer programming has been recommended as a development tool for expert systems and knowledge-based systems (Ruiz-Mier, Talavage, and Ben-Arieh 1985), system-theoretic modeling (Ziegler 1984) and programming in general (Cox 1983, Love 1983, Glinert and Tanimoto 1984, Finzer and Gould 1984). In this paper, we investigate the Smalltalk-80 object-oriented programming environment as a development tool for building simulation models. We attempt to achieve three goals in the paper. First we will briefly look at the features of the Smalltalk-80 object-oriented programming language. Second, the simulation control framework suggested by Goldberg and Robson (1983) as a Smalltalk-80 application will be investigated. A simulation model of the widget problem from Banks and Carson (1985) will be built in Smalltalk-80. Finally, we will look at the graphical features of Smalltalk-80 and compare the Smalltalk-80 environment to the environment of the traditional simulation software (i.e., GPSS/H, SIMSCRIPT II.5, SLAM II/TESS, SIMAN/CINEMA, SEE-WHY/WITNESS, and AutoMod/AutoGram).

2. Smalltalk-80 ENVIRONMENT

Smalltalk-80 language has a history of about 15 years (see Krasner 1983 for the evolution of the Smalltalk-80 language). The object-oriented paradigm of Smalltalk-80 language replaces the operator/operand concepts of conventional procedure-oriented languages with message/object concepts (Cox 1983, Pascoe 1986). In the operator/operand paradigm of procedure-oriented languages, operators are applied to the operands. For example, in the expression sin(theta), the operator sin is applied to the operand theta. The operand is passive and is passed to the operator. Operators, on the other hand, are active and make some predetermined change to the operand. The data-type assumptions of the operator have to be met by the operand and the environment is responsible for insuring it.

In the message/object paradigm of object oriented languages, objects (data) are asked to perform operations on themselves. The syntax of the object-oriented command is

object message.

To compute the sine of the number named **theta,** the command

theta sin

is used. The variable **theta** is asked to perform the **sin** operation on itself. That is, **theta** is the receiver of the message **sin.** The object **theta** is an instance of a class. Each object belongs to a class and a class may have multiple instances. It is the class of **theta** that provides the method for message **sin.** Methods are procedures that are invoked by sending messages to a class's instances. In other words, computation is performed by sending messages to objects, which invoke methods in their classes.

In Smalltalk-80, messages without arguments are called unary messages (i.e., **theta sin**). Messages with one or more arguments are called keyword messages. For example,

self holdFor: 0.04

is a single keyword message with the argument **0.04.** The receiver of the **holdFor:** selector is **self.** The double keyword message

self acquire: 1 ofResource: 'machine A'

has the selector **acquire:ofResource:.** The two arguments are **1 and 'machine A'** and the receiver of the message is **self.**

The methods of the above messages are defined in a class of Smalltalk-80. An implementation of the method for selector **holdFor:** is (Goldberg and Robson 1983),

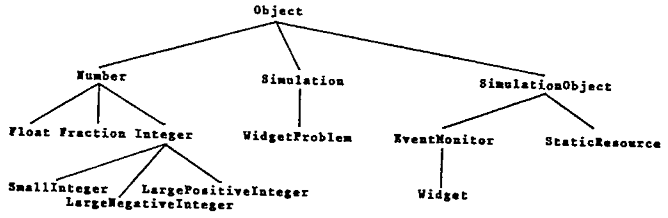
```
holdFor: aTimeDelay
  ActiveSimulation delayFor: aTimeDelay
```

where **aTimeDelay** is the argument of the method and refers to the argument of the actual message (i.e. **0.04**). The method for selector **holdFor:** sends to receiver **ActiveSimulation** the single keyword message **delayFor: aTimeDelay.** The method for selector **delayFor:** is described in some other class. Table 1 gives the methods of a chain of message-sends invoked by the selector **holdFor:** (Goldberg and Robson 1983). The corresponding class that defines each method is given too. Note that the method of selector **delayFor:** first sends the message **+ aTimeDelay** to **currentTime** and the value returned would be referred to as **aTime** in the method of selector **delayUntil:** (Parsing rules of Smalltalk-80 require binary messages to take precedence over keyword messages). There is no method description for **+** message since this is a Smalltalk-80 primitive method. Primitive methods are performed by the Smalltalk-80 virtual machine. Examples of messages in Table 1 that invoke primitives are **pause, new**, and **-**. There are about one hundred primitive methods in Smalltalk-80. In general, when an object receives a message, it sends other messages unless the method of the message contains only primitive methods. Each message-send eventually returns a result to the sender.

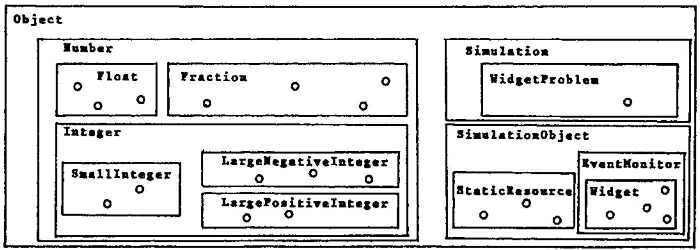
Smalltalk-80 system has a large number (over 200) of predefined classes of objects. These classes are arranged in a hierarchical order to facilitate the inheritance of the methods. Smalltalk-80 supports the subclassing form of inheritance for its classes. A subclass is contained completely within its superclass. In other words, if any instances of a class are also instances of a superclass, then all instances of that class must also be the instances of the superclass. The subclassing concept is illustrated in Figure 1 by the system class **Number** and the user defined classes **SimulationObject** and **Simulation.** In Figure 1(b) boxes represent classes and the small circles represent instances. Class **Number** has three subclasses; **Float, Fraction,** and **Integer.** Similarly, three subclasses are defined for class **Integer** too, namely;

Table 1: Methods of a Chain of Message-sends of Selector **holdFor:** (Goldberg and Robson).

```
Message Pattern                                          Class

holdFor: aTimeDelay                                      SimulationObject
  ActiveSimulation delayFor: aTimeDelay

delayFor: aTimeDelay                                     Simulation
  self delayUntil: currentTime + aTimeDelay

delayUntil:aTime                                         Simulation
  |delayEvent|
  delayEvent <-- DelayedEvent onCondition:
                                     aTime.
  eventQueue add: delayEvent.
  self stopProcess.
  delayEvent pause.
  self startProcess

onCondition:  onObject                                   DelayedEvent
  ↑super new setCondition:  an Object

setCondition:  anObject                                  DelayedEvent
  self initialize.
  resumptionCondition <-- anObject

initialize                                               DelayedEvent
  resumptionSemaphore <-- Semaphore new

stopProcess                                              Simulation
  processCount <-- processCount - 1

startProcess                                             Simulation
  processCount <-- processCount + 1
```



(a) Tree diagram of class hierarchy



b) Nested box representation of class heirarchy

Figure 1: Subclassing in Smalltalk-80

SmallInteger, **LargePositiveInteger**, and **LargeNegativeInteger**. A number in the system can be an instance of one of the five classes; **Float**, **Fraction**, **SmallInteger**, **LargePositiveInteger**, or **LargeNegative-Integer**. Classes **Number** and **Integer** are used to specify the shared methods of their subclasses and they don't have any of their own instances. Such classes are known as abstract superclasses. Class **Number** methods include all the arithmetic operations and mathematic functions (e.g., **exp**, **ln**, **sqrt**) On the other hand, class **Integer** defines methods which are unique to integers (e.g., **factorial**). Therefore, if an instance of class **SmallInteger** receives the message **sqrt**, it will look for **sqrt** method at its own class (i.e., **SmallInteger**) first, then at its superclass (i.e., **Integer**), and then at the superclass of its superclass (i.e., **Number**). The search for the method follows the superclass chain until the method is found or the class **Object** has been reached. Class **Object** describes the similarities of all objects in the system, so every class is at least a subclass of **Object**. In other words, **Object** is the single root class and the only class without a superclass.

In describing a class in Smalltalk-80, the programmer specifies the class name, its superclass, variable names, and a set of methods. Table 2 gives the description of class **Widget**. Its superclass is **EventMonitor**. A class may have two categories of variables; class and instance variables. Class variables are shared by all the instances of a class while the instance variables are unique to each instance. Instance variables exist only during the lifetime of the object . In Table 2, the class variable **WidgetCounter** is used to assign a sequence number to the **Widget** objects as they are created. The instance variable **entryTime**, on the other hand, stores the creation time of each **Widget** object. The methods of a class are also categorized into class methods and instance methods. Class methods are mainly used for creation of instances and the initialization of class variables. In Table 2, class initialization message category contains the message **file: aFile** to specify a file (i.e., **aFile**) for output data. Instance methods act uniquely for each instance of a class. For example, a **Widget** object may send the message **self holdfor: 0.04** while another **Widget** object may be sending the message **self release: holdAreaCell**. Note that the **Widget** objects have three message categories, namely, initialization, accessing, and simulation control. The "initialization" message category contains the method for message **initialize**, "accessing" contains the methods for **entryTime** and **setLabel**, and "simulation control" contains the method for **tasks**.

3. SIMULATION USING Smalltalk-80

In this section, we will first describe the simulation control framework suggested by Goldberg and Robson (1983) for Smalltalk-80. We will then use their control framework in building a simulation model for the widget problem given by Banks and Carson (1985).

Table 2: Implementation Description of **Widget** Class.

class name	Widget
superclass	EventMonitor
class variable names	WidgetCounter
instance variable names	entryTime

```
class methods

class initialization

  file: aFile
   super DataFile  <-- aFile.
   WidgetCounter <-- 0


instance methods

initialization

  initialize

    super initialize.
    entryTime <-- ActiveSimulation time

accessing

  entryTime

     ↑entryTime

  setLabel

     WidgetCounter <--WidgetCounter + 1.
     label <-- WidgetCounter  printString

simulation control

  tasks

     | conveyorCell  machineA  holdAreaCell  machineB |

       conveyorCell <-- self acquire: 1  ofResource: 'conveyor cells'.
       machineA <-- self acquire: 1  ofResource: 'machine A'.
       self release: conveyorCell.
       self holdFor:  0.04.
       holdAreaCell <-- self acquire: 1 ofResource: 'holding area cells'.
       self release: machineA.
       machineB <-- self acquire: 1 ofResource: 'machine B'.
       self release: holdAreaCell.
       self holdFor: 1/28.
       self release: machineB
```

The simulation control framework developed for Smalltalk-80 in Part 4 of Goldberg and Robson (1983) is based on the framework used by Demos (Birtwistle 1979). Goldberg and Robson (1983) indicate that theirs is only one of the many ways one can specify a simulation control framework for Smalltalk-80 language. The Smalltalk-80 language can be effectively used in developing a simulation control framework that has one or more of the "world-views" of simulation languages, including process interaction, activity scanning, or event scheduling approaches. The Smalltalk-80 language can also be used for discrete change, continuous change and combined discrete/continuous change models. The language does not currently come with the object classes that facilitate simulation model building. In other words, it is like using FORTRAN or PL/1 for simulation.

The simulation control framework suggested by Goldberg and Robson (1983) can best be described as object process interaction. Whether the object is a temporary entity (transaction) object (e.g., customers to be served, parts to be processed) or a permanent entity (resource) object (e.g., server, machine), one specifies the set of tasks that each object has to go through. Goldberg and Robson (1983) suggest this mechanism especially if the permanent entities have complex coordination requirements (they call these "coordinated resources"). On the other hand, permanent entities with simple interaction with temporary entities are not created, but a count is kept on their usage (Goldberg and Robson call these "static resources").

Goldberg and Robson (1983) describe seven main classes in their simulation control framework as depicted in Figure 2.

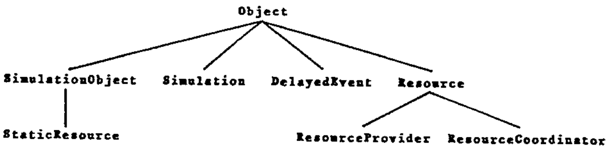


Figure 2: Seven Main Classes of the Simulation Control Framework (Goldberg and Robson 1983)

Classes **SimulationObject**, **Simulation**, **DelayedEvent**, and **Resource** are subclasses of **Object**. **SimulationObject** has one subclass **StaticResource** while **Resource** has two subclasses, **ResourceProvider** and **ResourceCoordinator**. Let us define each of these classes briefly. Class **SimulationObject** specifies a general kind of temporary entity object that might appear in a simulation. The methods of **SimulationObject** provide a general control sequence by which an object enters the system, carries out its tasks, and leaves the simulation. Table 3 gives the **SimulationObject** class implementation description partially in summary format. The **startUp**, **tasks** and **finishUp** messages of the simulation control message category of **SimulationObject** gives the general life-cycle of a temporary entity object in the model. The temporary entity objects defined by the simulation modeller for a specific problem can then be placed as a subclass of **SimulationObject** so that they inherit its generic methods (e.g., **holdfor:**, **acquire: ofResource:**, **release:**).

Class **StaticResource** is a **SimulationObject** that holds resource quantities for some other **SimulationObjects** that utilize these resources (e.g. hold a machine for a part while the part is being processed on that machine).

Class **Simulation** controls the simulation process and defines arrival schedules of **SimulationObjects**, creates resources, queues the delayed events and maintains a reference to **SimulationObject** for synchronization purposes. Table 4 gives a partial implementation description of class **Simulation** in summary format. Messages in the initialization category of **Simulation** initialize simulation variables, including

Table 3: Implementation Description of **SimulationObject** Class (Goldberg and Robson 1983)

```
class name              SimulationObject

superclass              Object

class variable names    ActiveSimulation


class methods

class initialization

      activeSimulation:  existingSimulation

instance creation

      new


instance methods

simulation control

     intialize

       ↑self                  "Let subclass initialize the instance variables"

     startUp

       ActiveSimulation enter: self.   "Let simulation class know I entered"
       self tasks.                     "Start performing the tasks"
       self finishUp.                  "Time to leave the system"

     tasks

       ↑self                          "Let subclass specify the tasks"

     finishUp

        ActiveSimulation exit: self   "Let simulation class know I am done"

task language

     holdFor:  aTimeDelay
     acquire:  amount of Resource:  resourceName
     release:  aStaticResources
```

Table 4: Implementation Description of **Simulation** Class (Goldberg and Robson 1983)

```
class name                    Simulation

superclass                    Object

instance variable names       resources      currentTime
                              eventQueue     processCourt


class methods

instance creation

      new


instance methods

initialization

    initialize
      currentTime <-- 0.0.     resources <-- Set new.
      processCourt <-- 0.      eventQueue <-- SortedCollection new

    activate

      SimulationObject activeSimulation: self. "Let SimulationObject know that"
      Resource activeSimulation: self          "this instance is active simulation"
                                               "Also let Resource know about active"
    define ArrivalSchedule                     "simulation"

      ↑self                                    "Let subclass specify the arrival of"
                                               "SimulationObjects"
    defineResources

      ↑self                                    "Let subclass specify the initially"
                                               "available resources"
task language

    produce: amount of: resourceName

scheduling

    delayUntil: aTime

    delayFor: timeDelay

    startProcess

    stopProcess

simulation control

    startUp
                                         "start simulation process"
      self activate.
      self defineResources.
      self defineArrivalSchedule

    proceed                              "Continue simulation process"

    finishUp                             "End the simulation"

    enter: anObject

    exit: anObject

accessing

   includesResourceFor:  resourceName

   provideResourceFor:   resourceName

   time

     ↑currentTime
```

the simulation time (**currentTime**) and the queue of simulation events to occur (**eventQueue**), and inform **SimulationObjects** and **Resources** about the specific simulation activated (message **activate**). Definitions of the arrival schedule of **SimulationObjects** and the resource definitions are left to the specific simulation model to be defined as a subclass of **Simulation**. The simulation control message category specifies the process that the simulation should go through from its start up to its end (messages **startUp**, **proceed**, and **finishUp**).

Instances of **DelayedEvent** are widely used for representing **SimulationObjects** that are delayed because they are getting service or because they are waiting for a resource to become available. Delayed tasks are the tasks of the **SimulationObjects** that are waiting for the time they should end. These are known as scheduled or voluntary waiting times in simulation. One example would be waiting for the end of service invoked by the message **holdFor:**. Involuntary waiting times are the waiting times due to unavailable resources. For example, a **Widget** object (Table 1) may wait to acquire resource **´machine A´** when executing its message

machineA <-- self acquire: 1 ofResource: ´machine A´ .

Class **Resource** and its subclasses **ResourceProvider** and **ResourceCoordinator** together with class **StaticResource** define the message protocols required for allocating static and coordinated resources in the model. The message protocol for static

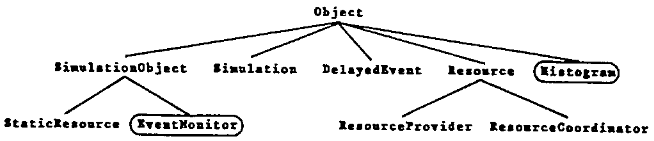


Figure 3: Simulation Control Framework Including the Statistics Gathering Classes (Goldberg and Robson 1983)

resources are defined in classes **StaticResource**, **Resource** and **ResourceProvider** while the coordinated resource messages are defined in classes **Resource** and **ResourceCoordinator.**

Goldberg and Robson (1983) also define a number of classes for collection of statistics in the simulation. Figure 3 depicts an updated simulation control framework class hierarchy including two classes related to collection of statistics (new classes are circled in Figure 3(a)). Class **Histogram** defines a histogram for a simulation statistic. Class **EventMonitor** is designed to trace the progress of simulation objects from their entrance to the model to their exit. It basically defines a file and overrides the messages of class **SimulationObject** so that it can store to the file information about the events that a **SimulationObject** goes through. For example, the message **holdFor:aTimeDelay** in Table 1 is overridden in class **EventMonitor** as (Goldberg and Robson 1983)

```
holdFor: a TimeDelay
    self timeStamp.
    DataFile nextPutAll: 'holds for'.
    aTimeDelay printOn: DataFile.
    super holdFor: aTimeDelay .
```

This message may produce a trace line in file **Datafile** that looks like

```
0.115232 Widget 2 holds for 0.04 .
```

The simulation control framework defined in Figure 3 gives the basic elements required to build a discrete-event simulation model of a system. First, the programmer has to specify the simulation control environment by defining the simulation problem as a subclass of class **Simulation.** Then, the programmer has to identify the temporary entity objects of the system and define them in a subclass of **EventMonitor** (or **SimulationObject,** if no trace needed). For similar objects, subclass hierarchies of class **EventMonitor** may be used. Finally, the programmer has to identify the permanent entity objects as resources. The programmer has the choice of using a static resource or a coordinated resource for each of the resources. In the case of complex interaction between the resource and the temporary entity objects in the model, one should choose a coordinated resource. For each coordinated resource used in the model, a simulation object has to be defined as a subclass of **EventMonitor.** On the other hand, if simple interaction exists between temporary entity objects and the resource, a static resource should be used. Counts, rather than simulation objects, are used for static objects.

4. THE WIDGET PROBLEM

In their paper, Banks and Carson (1985) compare the process interaction perspectives of GPSS/H, SIMSCRIPT II.5, SLAM II, and SIMAN simulation languages using a widget problem. We use a simplified version of the same widget problem in describing the simulation environment of Smalltalk-80. The widget problem assumes two serially connected machines, machines A and B. The widgets arrive randomly by conveyor to machine A at a Poisson rate of 17 per minute. The conveyor can hold a maximum of 50 widgets. Widgets arriving when the conveyor is full wait until a place becomes available on the conveyor. After processing at Machine A is completed, widgets go to machine B. The in- process storage area between machines A and B has a finite capacity of 40 widgets. If the storage area is full when a widget completes processing on machine A, then machine A becomes blocked. Processing rates at A and B are constant with rates 25 and 28 per minute, respectively. The machines process one widget at a time. The system will be started at time zero under empty and idle conditions. Statistics collected will include the histogram of the widget residence time.

The simulation process for the widget problem will be described in class **WidgetProblem** defined as a subclass of **Simulation.** The message protocol of class **Simulation** was given in Table 4 and it basically defined the default simulation control messages. Class **WidgetProblem** overrides these messages as required by the problem description. Table 5 gives the implementation description of the **WidgetProblem** class. The initialization message category of **WidgetProblem** describes three messages, namely; **initialize, defineArrivalSchedule,** and **defineResources.** The **initialize** message invokes two messages. First, it sends to its superclass, class **Simulation,** the message **initialize.** (**super** in message **initialize** is a Smalltalk-80 pseudo-variable that refers to the receiver of a message; it starts the search for the method in the superclass of the class containing the method in which **super** was used.) The **initialize** message in Table 5 resets the default value of instance variables of the simulation defined by **WidgetProblem** (i.e., **currentTime**, **processCount**, **resources**, and **eventQueue**). Second, it defines **statistics** as an instance variable that refers to a **Histogram** that tallies values in the range 0.05 to 0.21 in intervals of size 0.01. The **defineArrivalSchedule** message defines the arrival of **Widget** objects to the system according to an exponential distribution. The **defineResources** message defines the capacity of static resources in the model. The four static resources are labeled as **machine A**, **machine B**, **conveyor cells** and **holding area cells**. Note that in class **Simulation**, the **defineArrivalSchedule** and **defineResources** messages have no default methods. The subclasses are expected to define these methods. The scheduling category defines two messages using the selectors **exit:** and **printStatisticsOn:**. The **exit:** selector overrides the **exit:** message in class **Simulation**. It first calls the **exit:** message in **Simulation** and then it stores residence time of simulation object **Widget** into the histogram, **statistics**. The message **printStatisticsOn: aStream** is used to print the histogram into a file.

In the widget problem there is only one class of temporary entity objects in the system: the widgets. This is because the static nature of resources (machine A, machine B, conveyor and in-process storage) do not warrant the use of coordinated resources in the model. The implementation description of widget class was already given in Table 2. In Table 2, we have defined class **Widget** as a subclass of **EventMonitor** because we wanted to obtain a trace of the progress of **Widgets** in the model for model verification purposes. The **initialize** message of **Widget** assigns to variable **entryTime** the arrival time of the widget to the model. The accessing message category also has a message **entryTime** which basically returns the value of the variable **entryTime** to the receiver (Note that **entryTime** message was invoked in the method of the **exit: aSimulationObject** message in Table 5 to find the residence time of each **Widget** object.) The **setLabel** message is invoked in class **EventMonitor** to label each **Widget** with a sequence number for easy tracing of the individual **Widgets** in the system. The simulation control message category of **Widget** class contains the **tasks** message which describes the sequence of tasks that a **Widget** object has to perform from its entrance into the system to its exit. The method first defines four temporary variables enclosed within vertical bars. The temporary variable **conveyorCell** defines a space on the conveyor static resource labeled **conveyor cells**. If a **Widget** object is successful in acquiring a **conveyorCell**, it tries to acquire **machineA**. If successful, releases the **conveyorCell** and holds **machineA** for 0.04 time units. Finally, the **Widget** object releases **machineB** and leaves the system.

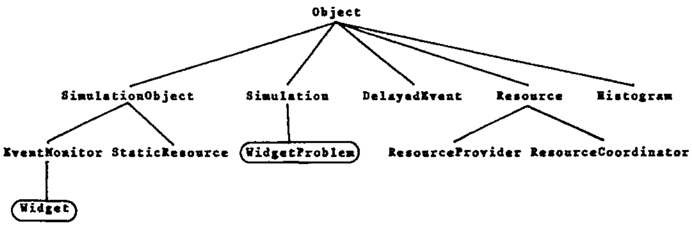
Table 5: Implementation Description of **WidgetProblem** class

```
class name                  WidgetProblem

superclass                  Simulation

instance variable names     statistics


instance methods

initalization

    initialize

       super initialize.
       statistics <-- Histogram from:  0.05 to: 0.21 by: 0.01

    defineArrivalSchedule

       self scheduleArrivalOf: Widget
            accordingTo: (Exponential mean: 1/17)

    defineResources

       self produce: 1 of: 'machine A'.
       self produce: 1 of: 'machine B'.
       self produce: 50 of: 'conveyor cells'.
       self produce: 40 of: 'holding area cells'

scheduling

    exit:  aSimulationObject

       super exit:  aSimulationObject.
       statistics store:  currentTime - aSimulationObject entryTime

    printStatisticsOn:  aStream

       statistics printStatisticsOn: aStream
```

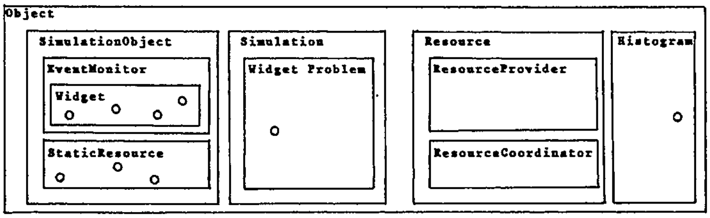
The development of the Smalltalk-80 simulation model for the widget problem required the inclusion of two additional classes to the simulation control framework class hierarchy discussed previously. Figure 4 shows the updated simulation class hierarchy for the widget problem. The circled classes in the tree diagram are the new additions to the simulation class hierarchy.

The simulation can now be invoked by creating an instance of **WidgetProblem** and sending the **startUp** message to it. One can then send the **proceed** message to the simulation to move the simulation from one event time to another. The messages below will run the simulation for 120 time units and store the trace and histogram outputs into two different files;

```
Widget file: (Disk file:
                  'WidgetProblem.trace').
aSimulation <-- WidgetProblem new
                  startUp.
[aSimulation time < 120] whileTrue:
                  [aSimulation proceed].
aSimulation printStatisticsOn:
           (Diskfile:'widget.report') .
```



(a) Tree diagram of class hierarchy



(b) Nested box representation of class hierarchy

Figure 4: The Class Hierarchy for the Widget Problem

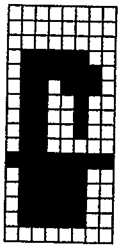
A portion of the output produced by the widget problem is given below.

Table 6: Simulation Output of Widget Problem

```
0 0 Widget 1 enters
0.0 Widget 1 requests 1 of conveyor cells
0.0 Widget 1 obtained 1 of conveyor cells
0 0 Widget 1 requests 1 of machine A
0.0 Widget 1 obtained 1 of machine A
0.0 Widget 1 releases 1 of conveyor cells
0.0 Widget 1 holds for 0.04
0.04 Widget 1 requests 1 of holding area cells
0.04 Widget 1 obtained 1 of holding area cells
0.04 Widget 1 releases 1 of machine A
0.04 Widget 1 requests 1 of machine B
0.04 Widget 1 obtained 1 of machine B
0.04 Widget 1 releases 1 of holding area cells
0.04 Widget 1 holds for (1/28)
0 0757143 Widget 1 releases 1 of machine B
0 0757143 Widget 1 exits
0.115232 Widget 2 enters
0.115232 Widget 2 requests 1 of conveyor cells
0.115232 Widget 2 obtained 1 of conveyor cells
0.115232 Widget 2 requests 1 of machine A
0.115232 Widget 2 obtained 1 of machine A
0.115232 Widget 2 releases 1 of conveyor cells
0.115232 Widget 2 holds for 0.04
0 1209 Widget 3 enters
0.1209 Widget 3 requests 1 of conveyor cells
0.1209 Widget 3 obtained 1 of conveyor cells
0.1209 Widget 3 requests 1 of machine A
0.155232 Widget 2 requests 1 of holding area cells
0.155232 Widget 2 obtained 1 of holding area cells
0 155232 Widget 2 releases 1 of machine A
0.155232 Widget 2 requests 1 of machine B
```

5. GRAPHICS AND Smalltalk-80

The principal facility in Smalltalk-80 for doing animation of discrete event simulations is the class **Form**. A **Form** is a rectangular array of pixels represented internally as a bitmap. A **Form** has a width and height, measured in pixels. The width and height also define the sizes of the two dimensions of the array of bits which constitutes the **Form**'s bitmap. A **Form** can be created, edited, translated, scaled, displayed, animated, and written to a disk file by means of messages that are built into the Smalltalk-80 system. Figure 5 depicts a **Form**.



array of pixels

```
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 1 1 1 1 1 0 0
0 1 1 1 1 1 1 0
0 1 1 0 1 1 1 0
0 1 1 0 0 1 0 0
0 1 1 0 0 1 0 0
0 1 1 0 0 1 0 0
0 1 1 0 0 0 0 0
1 1 1 1 1 1 1 1
0 1 1 1 1 1 0 0
0 1 1 1 1 1 0 0
0 1 1 1 1 1 0 0
0 1 1 1 1 1 0 0
0 0 0 0 0 0 0 0
```

bitmap

Figure 5: A **Form** of Width 8 and Height 16.

A new **Form** can be drawn interactively. The procedure is to first send the message **newForm** to class **FormEditor**. This opens the **FormEditor** with a blank drawing area to work in. Drawing in **FormEditor** is very similar to using drawing programs like MacWrite for personal computers (Lu 1984), although **FormEditor** doesn't have as many features. It is described fully in Goldberg (1984). Once the drawing is complete, the message that is actually used to create a new instance of class **Form** is **fromUser**. This message allows the user to select a rectangle of the screen whose pattern of black and white pixels will define the new **Form**. The message **fromUser** is one of several messages for creating new **Forms**. Others read the bitmap from a disk file to create a new **Form**, create new blank **Forms**, or create dots of varying radii.

A **Form** can be edited at any time by giving the messages **edit**, for editing using **FormEditor**, or **bitEdit**, for editing using **BitEditor**. **BitEditor** is similar to the FatBits option in MacPaint (Lu 1984); it allows a **Form** to be edited one pixel at a time for detail work. A **Form's** bitmap can be saved by means of the message **writeOn:** in a file that can be read by the instance creation message **readFrom:**. In this way a library of icons can be created.

The fundamental message for displaying **Forms** is **displayOn:at:clippingBox:rule:mask.** The usual argument for the **DisplayOn:** keyword is **Display**. The other keywords provide for control of the location (in screen coordinates) at which the **Form** will be displayed, the portion of the screen against which it should be clipped, whether it should be drawn over or under, erase, or combine in some other fashion with what is already on **Display**, and what color should be used. Smalltalk-80 supports only monochrome graphics, but it does provide patterns of black and white pixels that simulate four shades of gray for filling in areas. The message

```
   displayOn:  Display
          at:  100@100
 clippingBox:  Display boundingBox
        rule:  Form under
        mask:  Form lightGray
```

displays a **Form** on the screen at pixel location (100,100) in light gray according to the rule that only black pixels are allowed to affect whatever is presently displayed on the screen. Shorter forms of the **displayOn:...** message are also provided which supply defaults for some of the keywords. These messages, together with **magnifyBy:** and **shrinkBy:** provide the resources necessary to implement displaying, zooming and panning.

It is easy to place several **Forms** into an array as one of a **SimulationObject's** instance variables, corresponding to the states it can be in. For example, a **SimulationObject** representing a machine can have a **Form** for each of the four states busy, idle, starved, and undergoing repair. When a job is started, changing the object's state from idle to busy, the **Form** for busy is displayed over the **Form** for idle. Continuous motion can also be done for one **Form** at a time by using the message **follow:while:**.

6. TRADITIONAL SIMULATION SOFTWARE AND Smalltalk-80

Many features have been cited in the literature as being desirable in selecting a simulation package (Haider and Banks 1986, Grant and Weiner 1986). In this section, we will compare the Smalltalk-80 environment to the traditional simulation software environments in terms of the features deemed desirable for simulation model building and data analysis. The traditional simulation softwate to be considered are GPSS/H, SIMSCRIPT II.5, SLAM II/TESS, SIMAN/CINEMA, SEE-WHY/WITNESS, and AutoMod/AutoGram. The features to be discussed include modeling orientation, input flexibility, structural modularity, modeling conciseness, macro capability and hierarchical modeling, standard statistics generation and data analysis, animation, and interactive model debugging. (See Haider and Banks 1986 for a detailed description of these features.)

6.1 Modeling Orientation

In traditional simulation languages (SLs) the modeler is forced to map the simulation problem domain into the SL modeling orientation domain. The modeler has to decide whether a process interaction, event scheduling, or activity scanning approach is suitable for the problem. (Multiple modeling orientations are also possible for SIMSCRIPT II.5, SLAM II, and SIMAN.) Smalltalk-80 simulation environment supports an "object" process interaction approach where for each object a set of tasks are defined. Objects perform their tasks independently unless they need to be coordinated. They pass messages to each other to coordinate their work. This fits naturally to most of the discrete-event systems where there is an inherent message-passing orientation (e.g., manufacturing systems).

Special purpose simulation languages (SLs with preprocessors for specific problem domains) such as WITNESS and AutoMod/AutoGram remove the burden of model orientation selection as well as programming from the user. The disadvantage of such special purpose simulation languages is that they have limited application domains (Ulgen 1983).

6.2 Input Flexibility

Pre-formatted screens for model input are desirable features for programming efficiency. All SLs except GPSS/H and SIMSCRIPT II.5 appear to have this feature to some extent. Smalltalk-80 special purpose windows and pop-up menus create an excellent environment for development of flexible inputs to simulation models. CINEMA also has special-purpose windows and pop-up menus for animation layout design comparable to Smalltalk-80. For network models, SLAM II/TESS provides graphical model descriptions. SIMAN blocks can also be built interactively. WITNESS has a menu-driven input for model and display generations. Display generations are also interactive in AutoGram.

6.3 Structural Modularity

Structural modularity refers to the modular organization of the simulation software. Typical modules of a simulation software may inlude model processor, experiment processor, animation processor, run processor, and output processor. The advantage of structural modularity is that alterations can be done on one module without affecting others. It also reduces computer memory requirements, since one module executes at a time. The Smalltalk-80 environment gives to the modeler the capability to modularize the simulation environment to the above modules. The widget problem discussed in the paper had only three of the above modules, namely; model, experiment, and run processors. SIMAN software contains all the five modules given above. SLs with postprocessor animation (TESS and AutoGram) have their animation processors. All the SLs can be easily designed to have independent output processors.

6.4 Modeling Conciseness

Concise models are easier to build and verify. Process interaction modeling orientation with block, node, or user-written process routines enable development of concise models. The Smalltalk-80 model described in this paper uses process routines defined by the user. SIMSCRIPT II.5 also has the same feature. GPSS/H and SIMAN use block orientations while SLAM II uses node orientation. The event scheduling approaches seldom result in concise models when compared to process interaction models. The event scheduling approach is available in SEE-WHY, SIMSCRIPT II.5, SLAM II, and SIMAN.

6.5 Macro Capability and Hierarchical Modeling

Modular and hierarchical modeling based on system-theoretic concepts has been advocated by a number of researchers (Ziegler 1984, Oren 1984, Oren and Aytac 1985, Burns and Ulgen 1978). The Smalltalk-80 environment with its subclassing form of inheritance and object/message orientation supports a hierarchical model building approach. Macros of system components can easily be created and stored as objects and can be later modified with minimum effect on other model components. Traditional simulation software generally does not support hierarchical model building. Macros are available in all special purpose simulation languages (i.e., AutoMod). SIMAN and SLAM II are SLs that include macros for material handling components.

6.6 Standard Statistics Generation and Data Analysis

Traditional SLs provide comprehensive statistics on standard measures (e.g., resource utilizations, throughputs, wait times). They represent these statistics in terms of plots, histograms, etc. A Smalltalk-80 environment can be built to generate these statistics in many forms. Analysis of input and output data is possible with SLAM II/TESS. SIMAN includes an output processor for applying state-of-the-art statistical techniques to simulation output. Graphical output delineation is generally available with all animation software packages.

6.7 Animation

Grant and Weiner (1986) compare the animation features of a number of simulation software. Some of the simulation software for animation have specific problem domains while some are general purpose packages. AutoGram and WITNESS are limited to manufacturing and material handling systems. On the other hand, CINEMA, SEE-WHY, and TESS are general purpose animation packages. Smalltalk-80 has the capabilities for general purpose animation. Animation graphics can be concurrent (CINEMA, SEE-WHY/WITNESS, Smalltalk-80, TESS) or post-processed (AutoGram, TESS). Graphic displays of animation can be bit-mapped (Smalltalk-80, AutoGram, CINEMA, TESS) or character (SEE-WHY/WITNESS, TESS) graphics. Animation is an excellent communication and debugging tool. Zooming, panning, and having multiple displays increase the information to be obtained from animation. Zooming and panning capabilities exist in AutoGram, TESS, Smalltalk-80, and CINEMA. Multiple displays are available in CINEMA, SEE-WHY and TESS.

6.8 Interactive Model Debugging

Interactive model debugging and tracing are the tools for simulation model verification. Interactive debugging increases the efficiency of programmer. Smalltalk-80, GPSS/H, SIMSCRIPT II.5, SEE-WHY, SIMAN, and SLAM II all have interactive debugging features.

7. CONCLUSION

Smalltalk-80 environment has unique characteristics when compared to traditional simulation software. Its object/message paradigm and hierarchical class structure facilitates the modular and hierarchical model development. The description of temporary and permanent entities as objects, each with a set of tasks, creates a new type of process interaction modeling orientation (which we called "object" process interaction). The object process interaction appears to be a natural modeling orientation since one can identify a simulation object for each real system object.

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