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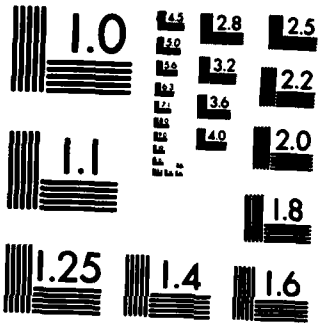

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This report provides an overview of ROSS, an object-oriented language currently being developed at Rand. The goal of ROSS is to provide a programming environment in which users can conveniently design, test, and modify large knowledge-based simulations of complex mechanisms. Object-oriented programming languages, and ROSS in particular, enforce a message-passing style of programming in which the system to be modeled is represented as a set of objects and their behaviors (rules for object interaction). This style is especially suited to simulation, since the mechanism or process to be simulated may have a decomposition that maps naturally onto objects, and the real-world interactions between the objects may be easily modeled by object behaviors and object message transmissions. In addition to describing some of the basic ROSS commands and features, the report discusses some software that interfaces directly with ROSS, including a sophisticated screen-oriented editor and a color graphics package. Facilities for browsing among objects and their behaviors are also described, and examples of browsing and editing are presented using SWIRL, a military combat simulation written in ROSS.

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ROSS: An Object-Oriented Language for Constructing Simulations

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December 1984

A Project AIR FORCE report
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PREFACE

As part of a concept-development effort within the Force Employment Program of Project AIR FORCE, Rand has been investigating techniques to improve computer technology for military combat simulations. This work has focused on developing a research environment that aids users in designing, building, understanding, and modifying battle simulations in order to analyze and evaluate various outcomes. Results of this work include the development of an English-like, object-oriented simulation language called ROSS; the design and implementation of a strategic air penetration simulation built in ROSS, called SWIRL; the design and implementation of a tactical ground-based combat simulation built in ROSS, called TWIRL; and the design of a parallel processing computer architecture for distributing simulations to significantly enhance their performance. These systems are reported in the following Rand publications:

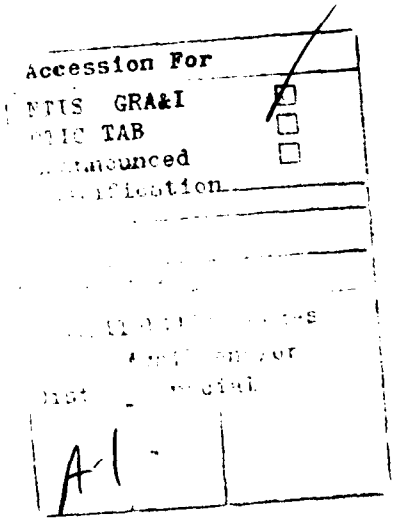
The ROSS Language Manual, by D. McArthur and P. Klahr, N-1854-AF, September 1982.

SWIRL: Simulating Warfare in the ROSS Language, by P. Klahr, D. McArthur, S. Narain, and E. Best, N-1885-AF, September 1982.

TWIRL: Tactical Warfare in the ROSS Language, by P. Klahr, J. Ellis, W. Giarla, S. Narain, E. Cesar, and S. Turner, R-3158-AF, October 1984.

Fast Concurrent Simulation Using the Time Warp Mechanism, Part I: Local Control, by D. Jefferson and H. Sowizral, N-1906-AF, December 1982.

This report provides an introduction to the ROSS language.



SUMMARY

This report provides an overview of ROSS, an object-oriented language currently being developed at Rand. The goal of ROSS is to provide a programming environment in which users can conveniently design, test, and modify large knowledge-based simulations of complex mechanisms.

Object-oriented programming languages, and ROSS in particular, enforce a *message-passing* style of programming in which the system to be modeled is represented as a set of *objects* and their *behaviors* (rules for object interaction). This style is especially suited to simulation, since the mechanism or process to be simulated may have a decomposition that maps naturally onto objects, and the real-world interactions between the objects may be easily modeled by object behaviors and object message transmissions.

In addition to describing some of the basic ROSS commands and features, the report discusses some software that interfaces directly with ROSS, including a sophisticated screen-oriented editor and a color graphics package. Facilities for browsing among objects and their behaviors are also described, and examples of browsing and editing are presented using SWIRL, a military combat simulation written in ROSS.

CONTENTS

I. INTRODUCTION

This report presents an overview of ROSS, an object-oriented simulation language. ROSS is one of the first languages that attempts to marry artificial intelligence (AI) methods with simulation technology. We have found that the marriage benefits both parties. Simulation is a powerful inference and design tool that has been largely overlooked by AI researchers; however, many human experts rely heavily on qualitative simulation to understand and fix complex systems. We believe that incorporating simulations as components would increase the power of many expert systems. But while simulation is potentially a powerful tool for modeling, understanding, and designing complex systems, present-day simulators do not have the necessary features to allow simulation to fulfill its potential. This report discusses these shortcomings and shows how ROSS uses AI techniques to create a simulation environment that overcomes many of the limitations. The report is not a manual providing detailed discussions of the commands or rationale of the ROSS language. Those discussions are provided in McArthur and Klahr (1982), and equally detailed discussions of specific simulations written in ROSS can be found in Klahr et al. (1982a, 1982b) and Klahr et al. (1984). The language and its applications are described here only to the degree necessary to provide a general overview.

SIMULATION AS A REASONING AND DESIGN TOOL

It is often useful to be able to understand a dynamic system without manipulating it in the real world. Some real-world systems perform too slowly (e.g., economic systems), some have dangerous consequences (e.g., nuclear reactors), and some are awkward or impossible to manipulate directly (e.g., the solar system). In such cases, it is desirable to be able to draw conclusions about the behavior of the system by reasoning with a model of the system, rather than by observing the system itself.

Model-based reasoning has many uses. Most basically, it can be used to understand and predict the performance of the system. When the system is one that can be modified by the user, model-based reasoning can also be used for intervention and design. In some systems, only limited changes are possible (e.g., a medical treatment modifies bodily processes in a constrained way), but in others, the user has full control over structural properties (e.g., the design of a computer). For systems that can be modified, conclusions drawn by reasoning about system behavior can be used as a basis for making coherent structural changes. These changes then lead to an examination of the behavior of the new system, and more rounds of changes. A successful *design cycle* ideally converges on a system that exemplifies some predetermined behavioral properties.

Unfortunately, the intuitive methods currently used to model systems are inaccurate and incomplete, while mathematical (analytic) methods, though accurate, may be of limited value because of the difficulty of formally modeling all the complexities of many dynamic systems. Simulation represents a useful tool for reasoning about the possible behaviors of dynamic

systems which potentially avoids the imprecision of intuition, while providing greater expressive power than mathematics.[1]

SHORTCOMINGS OF EXISTING SIMULATION TECHNIQUES

While simulation technology is potentially a powerful tool for modeling, understanding, and designing systems, large-scale simulators do not provide the features necessary to allow simulation to fulfill its potential. Four major shortcomings of present simulations and simulators are described below.

Inability to Verify the Completeness and Accuracy of Models

A large-scale simulator typically contains many types of knowledge that collectively comprise a model of a real-world system. Some types are explicitly represented and understandable, e.g., an object's properties, such as location, velocity, or altitude. Other types of knowledge, such as how objects behave, how they interact with other objects, and how they make decisions, may be impossible to understand. Users may have to search through volumes of manuals, looking for behavioral descriptions that are buried in incomprehensible code. Even if the information can be located and understood, the user cannot be sure that the system actually performs as specified. Much can get lost in the translation to computer code. Further, knowledge is typically not well structured. Embedded assumptions are hidden, scattered, and fragmented throughout the program. The initial structure of the first version of a simulation is often lost as more complexity is added or modifications are made. As a result, there is no assurance that the simulation embeds an accurate or complete model of the dynamic system. The user cannot have confidence in either the predictions or the design advice the simulation might suggest.

Inability to Modify Models and Construct Alternative Models

Models embedded in simulations cannot be easily modified, for many of the same reasons they cannot be verified for accuracy. If the key behaviors of simulation objects are hidden in masses of code—or worse, distributed across the code—users will not be able to alter them in a coherent fashion. The simulation may thus inhibit rather than promote the easy changes required to provide a good environment in which to investigate alternatives.

Incomprehensibility of Results

A simulation that is intelligible, and thus can be verified to represent an accurate model, can be confidently expected to produce data that describe the behavior of the modeled dynamic system. However, if the data are not presented effectively, it can be almost impossible to see the most important behavioral properties of the system. For example, large military simulations can generate hundreds of pages of numeric output for each simulation run. Determining the main global features of the simulation's performance from such output is a slow process at best; at worst, important trends may be overlooked entirely.

[1] We do not claim that simulation is the *only* means of modeling a system and drawing useful conclusions about its behavior, or even that it is necessarily the best means. Simulation is just one of many modeling tools; moreover, simulations do not enable users to answer several important kinds of questions about the system being modeled. For a more detailed discussion of the inherent limitations of state-transition simulations, see Davis et al. (1982).

Long Run Times

Even simulations that are intelligible and supply the support required to try out a wide range of alternatives are not useful if they are too slow. Certainly, simulations that have reached a final "production" state must execute rapidly. The analyst expects to simulate complex processes in minutes, not hours. On a more subtle level, it is frequently necessary to try out many parameter settings or investigate many alternative models to draw any reliable inferences from a simulation. Such multiple experiments are prohibitive if each run takes more than a few minutes. Unfortunately, many simulations run even slower than real time. (Our approach to speed is discussed in Jefferson and Sowizral (1982), and the speeds of several different implementations of a ROSS simulation called SWIRL are discussed in Narain et al. (1983).)

II. OVERVIEW OF THE ROSS LANGUAGE

The ROSS language (McArthur and Klahr, 1982) was designed at Rand to overcome some of the shortcomings of existing simulations and to provide a superior environment in which to model, understand, and design dynamic systems. ROSS relies heavily on recently developed AI techniques and expert-systems technology (Hayes-Roth et al., 1983).

ROSS is an *English-like, object-oriented language*. Several examples of its English-like flavor are given later in this report. More detailed examples are presented in Klahr et al. (1984) and especially in Klahr et al. (1982b), which discusses virtually all the code of the SWIRL simulation. The English-like nature of the code makes it readable, and makes the models embedded in it intelligible to users who may not be programming experts. ROSS's object-oriented nature, which is shared by the SMALLTALK (Goldberg and Robson, 1983), PLASMA (Hewitt, 1977), FLAVORS (Weinreb and Moon, 1981), and DIRECTOR (Kahn, 1979) languages, imposes a style of programming that is highly suited to simulation. Because ROSS is interactive (it is implemented in Lisp), a ROSS simulation can be interrupted while it is running, the state can be queried or the code modified, and the simulation can then be resumed. With compiled simulation languages, such as SIMSCRIPT (Kiviat et al., 1968), the user must specify a simulation and let it run to completion before making any modifications. Thus, alternate designs can be explored in ROSS substantially more quickly and easily. ROSS's interactive nature also makes the debugging of simulations much simpler and more rapid. Over the course of constructing large simulations, this can mean substantial savings in development costs.

To make simulation results more comprehensible, ROSS provides a tracing facility that produces textual simulation output. In addition, ROSS is directly linked to a "movie generator" and graphics facility, so that visual representations can be generated as the simulation is running. This visual presentation is invaluable in discerning global trends in simulation performance.

ROSS has been operational for several years and has been implemented in a wide variety of Lisps (Narain et al., 1983), including Maclisp, Interlisp-20, Vax-Interlisp, Interlisp-D, Franzlisp, and Zetalisp. An earlier ROSS simulation, called SWIRL (Strategic Warfare in the ROSS Language), for example, provides a prototype of a design tool for military strategists in the domain of air battles (Klahr et al., 1982a, 1982b). SWIRL embeds knowledge about offensive and defensive battle strategies and tactics. It accepts from the user a simulation environment representing offensive and defensive forces, and it uses the specifications in its knowledge base to produce a simulation of an air battle. SWIRL also enables the user to observe the progress of the air battle in time, by means of a graphical interface. Exploiting ROSS's ability to easily modify simulation objects and their behaviors, SWIRL encourages the user to explore a wide variety of alternatives and to discover increasingly effective options in offensive and defensive strategies. Below, we elaborate on the main features of ROSS that are used in SWIRL.

THE STRUCTURE OF OBJECT-ORIENTED SIMULATION MODELS: OBJECTS, MESSAGES, AND BEHAVIORS

Object-oriented simulation languages enforce a style of programming that parallels the way we intuitively think of the processes in the dynamic system we are modeling. Many systems are naturally described in terms of separate components. For example, a car engine includes a carburetor, a transmission, etc. Further, the behavior of the system typically arises as objects interact by transmitting forces or information to one another, or by coming into physical proximity. In ROSS, such systems are modeled in a very natural way by creating *objects* to model each of the components of the dynamic system, and by modeling the interactions between them as *message passing*.

In ROSS, messages are sent from one object to another, using the following kind of form:[1]

(1) **(ask fighter-base1 send fighter2 guided by gci3 to penetrator4).**

The general syntax for message transmissions is:

(2) **(ask** <*object*> <*message*>**)**

where <*object*> is the name of any ROSS object or actor, and <*message*> is any sequence of Lisp atoms defining a legal ROSS message. In (1) above, the object named *fighter-base1* receives the message *send fighter2 guided by gci3 penetrator4.*

When an object receives a message, it must have a way of responding. The user therefore must define a *behavior* whose *pattern* matches the message and whose *actions* represent the appropriate response. In this case, the behavior might be:

```
(3) (ask fighter-base when receiving
        (send >fighter guided by >gci to >penetrator)
    (ask !myself schedule after
            !(ask myself recall your scramble-delay) seconds
            tell !fighter chase !penetrator guided by !gci)
    (ask !myself add !fighter to your list of fighters-scrambled)
    (ask !myself remove !fighter from your list of
            fighters-available)).
```

More generally, behaviors, like all computation in an object-oriented language, are defined by message transmissions of the form:

(4) **(ask** <*object*> **when receiving** <*message-template*> <*body*>**)**

where <*object*> is the name of any ROSS object or actor, <*message-template*> is any sequence of Lisp atoms defining a legal ROSS message, possibly including variables, and <*body*> is any arbitrary ROSS or Lisp code.

Just as ROSS objects are meant to model components of a real-world system, behaviors model the repertoire of ways that particular kinds of objects can respond to different inputs,

[1] Reserved ROSS keywords are shown in boldface.

information, or forces in the real world. Note that behaviors are attached to specific objects; they are not global functions. This captures the notion that different kinds of real-world entities have different behavioral capabilities.

When the message in (1) is sent, fighter-base1 will *pattern-match* that message (i.e., *send fighter2 guided by gci3 to penetrator4*) against the message templates of all the behaviors it knows, until it finds the appropriate one, in this case, *send >fighter guided by >gci to >penetrator*. This template matches the message because all the words in it are either identical to analogous items in the message or are *variables*. Variables are indicated by the prefixes > or +, and they match any word in the incoming message. Thus, *>fighter* matches *fighter2*, and the variable *fighter* will be bound to *fighter2* during the execution of the behavior associated with this template. (Similarly, *gci* will be bound to *gci3*, and *penetrator* will be bound to *penetrator4*.) Pattern variables such as *fighter* are prefixed by ! in the behavior body. This prefix forces the variable to be evaluated, i.e., its value is used, not its name (ROSS is a nonevaluating form of Lisp[2]). The behavior body itself embeds message transmissions, either to the object that received the current message (the object is always the value of the variable *myself*) or to any other object. Thus, a single message transmission can trigger an arbitrarily complex chain of subsequent transmissions.

OBJECT HIERARCHIES AND INHERITANCE

Another important semantic concept in ROSS is that of object hierarchies and inheritance. In item (1) above, a message was sent to an object called *fighter-base1*, while in (3), the user defined a behavior for an object called *fighter-base*. How can *fighter-base1* use a behavior that was defined for *fighter-base*? The answer is that although *fighter-base1* was not given this behavior directly, it can *inherit* it. To understand how inheritance works in ROSS, we need to understand how objects are created.

Objects can be created by forms such as

(5) **(ask** fighter-base **create instance** fighter-base1).

This message causes *fighter-base1* to be created as an instance of *fighter-base*. Semantically, *fighter-base* should be interpreted as denoting the class of all fighter-bases, while *fighter-base1* denotes a particular element of that class. This fundamental distinction between *generic* and *instance* objects is very useful in modeling real-world systems, which have different kinds of components, each instance of which has the same or similar properties. For example, all dogs (at least all healthy, normal dogs) have four legs, and most dogs bark when they see the mailman. A good modeling language should provide a way to make these quantified statements and to infer their truth for any particular dog. By allowing the creation of generic objects, ROSS provides a means of making quantified statements; by allowing inheritance, ROSS enables these statements to be instantiated for individuals.

The procedure of inheritance that models this instantiation is very simple. If an object (e.g., *fighter-base1*) has been created as an instance of a class (e.g., *fighter-base*), when the instance receives a message, it first looks at behaviors that have been explicitly attached to it,

[2]Lisps come in two basic types: evaluating and nonevaluating. An evaluating (or EVAL) version evaluates arguments to function calls before giving them to the function; a nonevaluating (or EVALQUOTE) version does not. For example, the EVALQUOTE form *list(a b)* and the EVAL form *(list 'a 'b)* both give the same result, namely a list of two elements, *a* and *b*.

to find one that matches the message. If it fails, it will consult the behaviors of the class objects of which it is an instance.

Simple inheritance has been generalized in two ways in ROSS. First, class objects may be subclasses of other objects, just as instances are members of classes. To create a subclass, one might say

(6) **(ask** fighter-base **create generic** prop-fighter-base)

(7) **(ask** fighter-base **create generic** jet-fighter-base).

This would indicate that there are two different kinds of fighter-bases, those that handle jets and those that do not. The importance of subclassing is that it allows users to express quantified statements of arbitrarily limited scope. There may be some things that all fighter-bases can do, some that only jet bases can do, and some that only prop bases can do.

Subclassing can be complex in ROSS, inducing a class-inclusion *object hierarchy*. An example of the object hierarchy used in SWIRL is shown in Fig. 1. When an instance of a generic object in this hierarchy receives a message, it does an inheritance search up from its location in the leaves of the hierarchy, to find an ancestral object that has a behavior matching the message it has received. Thus when matching an incoming message, *fighter-base1* will search, in order, object behaviors for *fighter-base1, fighter-base, fixed-object,* and *simulator.*

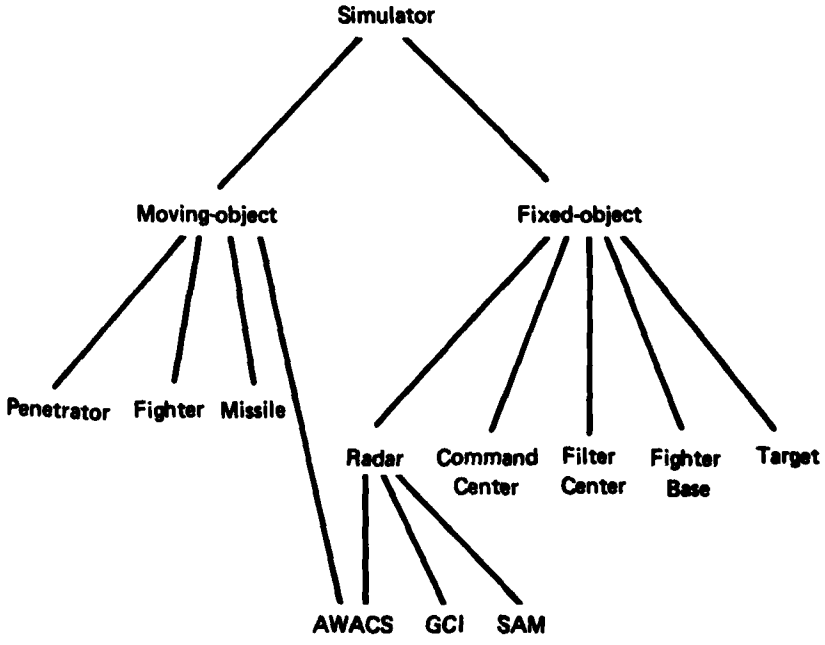


Fig. 1—SWIRL hierarchy of basic objects

The object hierarchy in Fig. 1 is not strictly a tree. *AWACS* (a type of airborne radar) is a subclass of both *moving-object* and *radar*. This *multiple inheritance* is the second way simple inheritance has been generalized in ROSS. Multiple inheritance was not a feature of earlier object-oriented languages, but it has proven highly useful in our ROSS simulations. Its value derives from the fact that it is often useful to view an object from multiple perspectives, or as being described in several ways, not as a fixed kind of thing. From one perspective, an AWACS can be viewed as having the properties of an aircraft, or a moving object; from another perspective, it can be viewed as a detector of electronic signals, or a radar.

Finally, although we have been talking primarily about the inheritance of behaviors, ROSS objects also possess attributes, and they too can be inherited. The behaviors of ROSS objects model the dynamic actions and reactions of real-world entities, i.e., how they respond to various inputs; the attributes of ROSS objects model the static features or properties of such objects (which may, however, dynamically change during a simulation). For example, we might have created the class object *fighter-base* as follows:

```
(8)  (ask fixed-object create generic fighter-base with
       position              (0 0)     ;position
       status                active    ;active or destroyed
       filter-center         nil       ;each base has one
       fighters-available    nil       ;list of free fighters
       fighters-scrambled    nil       ;occupied fighters
       fighters-destroyed    nil       ;its fighters lost
       scramble-delay        10        ;time to scramble once told
       alert-delay           10        ;delay to alert
       alert-duration        1800      ;how long to remain alert
       range                 400.0)    ;how far its fighters can go
```

Now, when *fighter-base1* wants to find out its alert-duration, it uses the message transmission

```
(9)  (ask fighter-base1 recall your alert-duration)
```

to find the value associated with *fighter-base*, effectively making the inference that since all fighter-bases have an alert-duration of 1800 seconds, it must have an alert-duration of 1800 seconds. Some of the attributes of *fighter-base* are to be interpreted as defaults, rather than as required values. For example, although all fighter-bases have an alert-duration of 1800 seconds, the position of a particular fighter-base can only be inferred to be (0 0) if no other information about that base is available, that is, if the base does not have a position explicitly associated with it. Also note that some attributes are known to exist but are not given any default values. These attributes have a *nil* initial value. When *fighter-base* is asked to create instances of itself, values for these attributes must be specified.

ROSS provides commands to create and manipulate the attributes of objects. For example, the message

```
(10)  (ask fighter-base1 set your status to destroyed)
```

will set the *status* attribute of *fighter-base1* to be *destroyed*. (If the particular attribute does not exist for the object, it is created.) The following message shows an example of modifying an inherited attribute:

(11) **(ask fighter-base1 increment your alert-duration by 100).**

If *fighter-base1* did not have a value for the attribute *alert-duration*, it would inherit the value of 1800 seconds from the *fighter-base* class to which it belongs, add 100 to it, and incorporate the result, 1900, as the value of its *alert-duration* attribute (without effecting any attributes of *fighter-base*). Attributes can be created and manipulated dynamically within a simulation or by a user at any time.

GETTING SIMULATIONS STARTED: PLANNING AND THE CLOCK

We have described computation in ROSS, but not simulation. A simulation language must provide a way of modeling events occurring over time. ROSS provides two such facilities. First, ROSS allows any object to plan an event to happen at any future time, using commands of the form

(12) **(ask fighter-base1 plan after 20 seconds**
tell fighter1 chase penetrator2 guided by gci3).

Once *fighter-base1* has issued this command, ROSS will ensure that the message embedded in the plan is sent to *fighter1*, not immediately, but after 20 seconds. (Of course, "20 seconds" refers to *simulated* real time, not real time or CPU time). Operationally, this means that all messages planned to be sent 19 seconds or less in the future are guaranteed to be sent before this message, and all planned for 21 seconds will be sent after it.

To execute planned events, ROSS provides a clock. The clock is a primitive ROSS object (called *nclock*) that advances simulation time when given commands such as

(13) **(ask nclock tick).**

A "tick" is a variable number of seconds, determined by the *ticksize* attribute of *nclock*. When the clock ticks, it not only advances simulated real time by a given interval of time, it also sends each of the messages (in time order) that have been planned for the current time interval. For example if (12) then (13) were issued at time 120 with a clock ticksize of 25 seconds, the simulated real time would first advance to 140 seconds (the time of the next message to be sent in the current time interval); the message embedded in (12), i.e., *tell fighter1 chase penetrator2 guided by gci3*, would be transmitted; and finally, the clock would advance to 145 and end the current tick.

The user can control the size of a tick by giving commands such as

(14) **(ask nclock set your ticksize to 20).**

Because the user can decide how many ticks to execute at a time and can specify the size of a tick, he has complete control over the "grain" of the simulation. At one extreme, he can let a

simulation run to completion without interruption; at the other, he can stop it after a very short duration, examine the state of any of the simulation objects in detail, and then resume running.

ADVANTAGES AND DISADVANTAGES OF OBJECT-ORIENTED LANGUAGES FOR SIMULATION

The main advantage of object-oriented languages for simulation is that they immediately suggest a way to view the dynamic system to be modeled. Our experience with SWIRL (Klahr et al., 1982a, 1982b) and TWIRL (Klahr et al., 1984) indicates that an object-oriented style of computation is especially suited to simulation in domains that may be thought of as consisting of autonomous *intentionally* interacting components. In such domains, the programmer can discern a natural mapping of their constituent components onto objects and of their intentional interactions, such as communication, *onto* message transmissions. Indeed, experts in many domains may find the object-oriented metaphor a natural one around which to organize and express their knowledge (Klahr and Faught, 1980).

However, in developing simulations in ROSS, we have discovered some events, or interactions between real-world objects, that are not as easily modeled as we might like them to be. These events are often side effects of deliberate actions (e.g., a penetrator appearing as a blip on a radar screen is a side effect of the penetrator flying its course and entering a radar range). Such events are important, since they may trigger other actions (e.g., a radar detecting a penetrator and notifying a filter center). However, these *nonintentional* events do not correspond to real-world message transmissions (e.g., a penetrator does not notify a radar that it has entered the radar's range). An important issue in the development of SWIRL has been the problem of capturing these nonintentional events in an object-oriented framework (i.e., via message transmissions). This problem and its various possible solutions are discussed in Klahr et al. (1982b).

ENGLISH-LIKE CODE IN ROSS

While the style of programming enforced by ROSS's object-oriented nature is the most important factor contributing to the modifiability of ROSS models, the highly readable character of the code is also important. Two features make ROSS code English-like. First, because behavior invocation uses pattern-matching, the user can define arbitrarily verbose behavior templates if he wishes. Thus, in (3) above, the user employed the template

(15) (send >fighter guided by >gci to >penetrator)

rather than the less English-like and less comprehensible

(16) (send >f guided-by >g >p)

even though either is quite acceptable as a ROSS command. If one were to implement behaviors in Lisp as functions, the resulting function calls would about as unintelligible as the code in (16):

(17) (send-guided-by-to fighter gci penetrator).

ROSS allows for even greater readability through its *abbreviations package*. This package was used in the development of SWIRL and TWIRL to generate code that would be comprehensible to strategic and tactical warfare experts who were programming novices. For example, after specifying the following abbreviations:

```
(18) (abbreviate '(ask !myself) 'you)
     (abbreviate '(ask !myself recall your) 'your)
     (abbreviate '(!) 'the)
```

we could rewrite (3) as

```
(19) (ask fighter-base when receiving
         (send >fighter guided by >gci to >penetrator)
       (~you schedule after !(~your scramble-delay) seconds
         tell ~the fighter chase ~the penetrator guided by ~the gci)
       (~you add ~the fighter to your list of fighters-scrambled)
       (~you remove ~the fighter from your list of fighters-available)).
```

The ROSS abbreviations package allows for *personalized* English-like programming, in contrast to languages like ROSIE (Fain et al., 1981), whose English-like syntax is fixed by the language designers. A personalized English syntax enhances the writability of code, whereas languages whose syntax is fixed often prove difficult to use because the user falsely assumes that *his* English syntax is the language's. In ROSS, this problem does not exist, because the user *does* define his own language syntax.

Second, even extensive use of the ROSS abbreviations package carries almost no computational overhead. ROSS expands the abbreviations only once, at load time, somewhat like displacing macros. Other English-like languages may incur high costs in parsing time. In fact, more time can be spent parsing the English-like surface representation into a machine-runnable form than actually executing the runnable code.

INTERACTIVE BROWSING AND EDITING FACILITIES

ROSS encourages the development of highly structured, interactive *browsing* and *editing* facilities. An interactive browser can be thought of as an interface that is an expert in the structure of a simulation and so can quickly guide even a naive user to any piece of a simulation model—any object or behavior. An interactive editor extends the browser by permitting the user to modify the code, once he has found the part of the simulation model he wishes to change. Collectively, these features facilitate rapid, coherent modification of models by users who are familiar with the *models*, but not necessarily with the specifics of their *implementation*.

Figure 2 shows a user interaction with a simple but effective browser we constructed for the SWIRL simulation. Item (20) is the top-level menu. (Virtually all user interaction with SWIRL involves menu selections.) The user selects option 9, which invokes the browser to guide him through the code. If the user has been interacting directly with ROSS, and not with the SWIRL menu, the browser could have been invoked by "(ask browser help)." The browser is a full-fledged ROSS object. At (21), the browser presents a menu of all SWIRL objects it

(20) Select option:
1—Break into ROSS
2—Load compiled SWIRL
3—Load interpreted SWIRL
4—Recompile interpreted SWIRL files
4—Recompile interpreted SWIRL files
5—Load a simulation environment
6—Run simulation with graphics
7—Run simulation without graphics
8—Activate historian and reporter
9—Browse or edit behaviors
10—Exit SWIRL & ROSS **9**

(21)
1.—PENETRATOR
2.—FIGHTER
3.—GCI
4.—SAM
5.—AWACS
6.—RADAR
7.—FILTER-CENTER
8.—COMMAND-CENTER
9.—FIGHTER-BASE
10.—TARGET
11.—MISSILE
12.—MOVING-OBJECT
13.—FIXED-OBJECT
14.—SCHEDULER
15.—PHYSICIST
16.—MATHEMATICIAN
Give number of object you wish to examine, or NIL to stop: **6**

(22) Documentation is available on the following templates:
1.—(>THING IS IN YOUR RANGE)
2.—(TRANSMIT TO YOUR FILTER-CENTER THAT +MESSAGE)
3.—(>PENETRATOR IS OUT OF YOUR RANGE)
4.—(TRY TO CHANGE GUIDER OF >FIGHTER TO >PENETRATOR)
5.—(>PENETRATOR IS DESTROYED)
6.—(>PENETRATOR HAS CHANGED ROUTE)
7.—(IS >PENETRATOR STILL IN YOUR RANGE)
8.—(GUIDE >FIGHTER TO >PENETRATOR)
9.—(STOP GUIDING >FIGHTER)
10.—(FIND A NEW GCI TO GUIDE >FIGHTER TO >PENETRATOR)
11.—(>FIGHTER HAS SIGHTED >PENETRATOR)
12.—(>FIGHTER UNABLE TO CHASE >PENETRATOR)
13.—(ARE SATURATED)
14.—(ARE NOT ECMED OUT BY >PENETRATOR)
15.—(CHECK FOR NEW PENETRATORS)
Give list of messages you wish to examine, or T for all, or NIL to stop: **8**

Fig. 2—Trace of interactive browsing in ROSS and SWIRL
(user's menu selections in boldface)

```
(23)        1.—ENGLISH DESCRIPTION
            2.—SWIRL CODE
            3.—BOTH
        Type option, or NIL to stop:  1

        (ask radar documentation for
            (guide >fighter to >penetrator) is

    |Sender: fighter or another radar handing over guidance of a fighter.
    Guides a fighter to a pen. Four cases arise: If the radar is destroyed
    it can do nothing. The fighter just follows unguided policy.
    If the fighter seeks guidance towards a penetrator that is not currently
    tracked by the radar, it tries to find another radar to guide the
    fighter. If this fails, it tells the fighter to follow unguided policy.
    If the radar is blinded, it tries to find another radar to guide the
    fighter. If this fails, it tells the fighter to follow unguided policy.
    Otherwise the radar calculates an intercept point of the fighter
    with the penetrator and tells fighter to vector to this point.|)
```

Fig.2—(continued)

knows about, and the user picks the one that he wishes to examine. At (22), the message templates of the selected object are displayed, and again the user selects one. Note how both the object-oriented structure of the simulation and the English-like nature of the message templates facilitate finding the exact part of the simulation the user wishes to examine. The object-oriented structure imposes a highly modular decomposition of the model, while the English-like templates make apparent exactly which behaviors are being modeled. At (23), the user chooses simply to see if the selected behavior embeds the right model. Had he selected option 2, ROSS would have put him into an editor with the code for the behavior.

USING ROSS IN THE EMACS EDITOR

ROSS is an interactive programming environment, since it is implemented in Lisp. We have discussed several examples of how this interactivity assists the user in understanding his simulations. However, standard interactive programming environments have limitations, most of which stem from the "typewriter" mode of interaction almost all current software enforces. Even though most users run Lisp and ROSS on a terminal with a screen, the screen is useless. Like a typewriter-based terminal, only the current line can be submitted for evaluation. Previous lines cannot be referenced.

We sought to make ROSS a fully screen-oriented interactive environment in several ways. First, we wanted to make each command on the screen referenceable. Second, we wanted to give the user the ability to create multiple windows on the screen, each associated with a different process, such as an editor, a compiler, or a ROSS program. Finally, we wanted to allow users to "program by pointing." The user should be able to move a cursor to any expression on the screen and tell ROSS what he wants done with the expression.

To achieve these goals, we modified ROSS to run as a process under Emacs (Gosling, 1981), a customizable, screen-oriented editor. In this environment, ROSS is inside an Emacs window, and all forms typed go into the window's buffer. When the user types a carriage return, Emacs takes the form just typed and submits it to the ROSS process for evaluation, printing the value returned just below the form submitted. Thus, in simple interactions, the environment looks just like a standard Lisp session. However, because the user is in a screen-oriented editor, several new capabilities are available. Emacs commands can be used to move the cursor to and mark any previous form in the ROSS buffer. Emacs commands can then be used to apply several operations to the marked item, including the following:

- *Evaluate the item.* If the marked item is a legal Lisp or ROSS form, it can be resubmitted to the ROSS interpreter, and its value will be returned. The expression can be edited with any standard editor commands before reevaluation.
- *Compile the item.* If the marked item is the name or definition of a Lisp function or ROSS behavior, a few keystrokes will tell Emacs to create a Lisp compiler process, associate it with a new window, submit the marked definition to the process, and return the result. In this way, compilation can be much more incremental and interactive than many Lisp dialects permit.
- *Edit the item.* If the marked item is the name or definition of a Lisp function or ROSS behavior, the user can request Emacs to visit the file that contains the function or behavior. The user does not need to know where the function or behavior is defined. Emacs will create a window for the appropriate file and put the user in the file at the location of the specified definition. When the user is in this window, all the above capabilities are still at his disposal, in addition to the basic editor commands for deleting, adding, moving, and searching text. In particular, he can point to parts of definitions and ask for them to be evaluated. In this fashion, definitions can be rapidly and incrementally modified.
- *Reformat the item.* If the marked item is a Lisp expression, a single command can be used to reformat the expression in a more readable way. This facility is especially useful for cleaning up function or behavior definitions in their files.

The ROSS-Emacs facility reduces the model-builder's memory load by remembering the location of definitions. At the same time, it makes the examination and modification of models a rapid process by automatically handling many low-level programming details.

TEXTUAL OUTPUT FACILITIES

We have discussed several features of ROSS that enable even naive users to locate, understand, and change complex simulation models. We now discuss some ways in which ROSS simplifies the analysis of simulation results, which too can be complex.

First, the interactive browsing in ROSS is easily extended to recording simulation events. For example, the recorder and historian we constructed for SWIRL work almost exactly like the browser. The recorder and historian are invoked by selecting option 8 in the SWIRL menu (item (24) in Fig. 3). Like the browser, the recorder and historian know all the objects and behaviors that comprise the SWIRL simulation and can guide the user through the code by displaying menus. The menus at (25) and (26) are similar to those at (21) and (22) in Fig. 2. However, when the user selects a behavior, the recorder and historian do not display the behavior, as the browser does; rather, they keep a record of each time that behavior is executed

(24) Select option:
1—Break into ROSS
2—Load compiled SWIRL
3—Load interpreted SWIRL
4—Recompile interpreted SWIRL files
5—Load a simulation environment
6—Run simulation with graphics
7—Run simulation without graphics
8—Activate historian and reporter
9—Browse or edit behaviors
10—Exit SWIRL & ROSS **8**

Specify file to record history: **RECORD**

Output to terminal (T or NIL): **T**

(25)
1.—PENETRATOR
2.—FIGHTER
3.—GCI
4.—SAM
5.—AWACS
6.—RADAR
7.—FILTER-CENTER
8.—COMMAND-CENTER
9.—FIGHTER-BASE
10.—TARGET
11.—MISSILE
12.—MOVING-OBJECT
13.—FIXED-OBJECT
14.—SCHEDULER
15.—PHYSICIST
16.—MATHEMATICIAN
Give list of objects in parentheses, e.g., (1 4 8), or NIL: **(1 2 4 5 6 7 9)**

(26) PENETRATOR has the following message templates:
1.—(FLY TO >PLACE)
2.—(DROP >M MEGATON BOMBS EXPLODING AT ALTITUDE >H)
3.—(>RADAR IS NOW TRACKING YOU)
4.—(>RADAR IS NO LONGER TRACKING YOU)
5.—(EVADE)
6.—(RESCHEDULE YOUR NEXT SECTOR)
7.—(MAKE A RANDOM TURN)
8.—(MAKE A TURN >N DEGREES >DIRECTION)

Give list of message numbers to record (T for all): **T**

Fig. 3—Trace of interactive recording in ROSS and SWIRL
(user's menu selections in boldface)

[User and recorder interact to specify trace for other objects]

.
.

Select option:
1—Break into ROSS
2—Load compiled SWIRL
3—Load interpreted SWIRL
4—Recompile interpreted SWIRL files
5—Load a simulation environment
6—Run simulation with graphics
7—Run simulation without graphics
8—Activate historian and reporter
9—Browse or edit behaviors
10—Exit SWIRL & ROSS **7**

(27) Type number of ticks to run: **100**

(28) 0.0 (AWACS3 LOOK FOR PEN3)
0.0 (AWACS3 LOOK FOR PEN2)
0.0 (AWACS3 LOOK FOR PEN1)
0.0 (AWACS2 LOOK FOR PEN3)
0.0 (AWACS2 LOOK FOR PEN2)
0.0 (AWACS2 LOOK FOR PEN1)
0.0 (PEN3 FLY TO (880.0 210.0))
0.0 (PEN2 FLY TO (352.0 700.0))
0.0 (GCI3 IS PEN2 STILL IN YOUR RANGE)
0.0 (GCI2 IS PEN2 STILL IN YOUR RANGE)
0.0 (PEN1 FLY TO (220.0 1085.0))
492.891342 (AWACS1 PEN2 IS IN YOUR RANGE)
492.891342 (AWACS1 ARE NOT ECMED OUT BY PEN2)

.

[Simulation continues for 100 ticks]

.

Select option:
1—Break into ROSS
2—Load compiled SWIRL
3—Load interpreted SWIRL
4—Recompile interpreted SWIRL files
5—Load a simulation environment
6—Run simulation with graphics
7—Run simulation without graphics
8—Activate historian and reporter
9—Browse or edit behaviors
10—Exit SWIRL & ROSS **10**

Fig. 3—(continued)

during a simulation. An example of a partial record is shown at (28) in Fig. 3. It indicates both the simulation time at which the behavior was invoked and the message transmission that caused the invocation.

The recorder and historian allow simulation output to be tailored in several ways. First, because the specification of the objects and behaviors to record is done interactively, recording can be interwoven with running of the simulation (see (27) in Fig. 3). Thus, the user can rapidly change the parts of the simulation model he is examining. Second, the user has a great deal of control over which message transmissions are traced. In standard procedural languages, the only option available is to trace a function or not to trace it. Object-oriented languages like ROSS allow the user to trace all the message transmissions for all instances of a given class of object, or a specific message transmission for all instances of a class, or even particular types of message transmissions for specific instances of a class of objects. For example, in SWIRL one can focus on just the activities of *fighter1*, rather than all fighters.

GRAPHICAL OUTPUT FACILITIES

A primary component of both the SWIRL and TWIRL simulations is their color graphics output facility. Although the graphics package is not an integral part of the ROSS language, we have developed a clean and direct interface between it and ROSS.[3] For each ROSS object, we define a symbol and color. Similarly, we define symbols for events that we wish to see graphically represented (e.g., communications between objects, military combat, radar detections). Each time the clock ticks, the graphics screen is updated to show the new locations of the objects and any new events that have occurred since the last clock tick. In a sense, the graphics package creates an animated movie of the simulation as it proceeds over time.

Graphics has provided us with a powerful tool for building and understanding simulations. Being able to watch the simulation as it is running enables the user to readily test out and verify behaviors, notice global interactions among the objects and events, zoom in on particular areas of interest, and determine the effects of alternative models and behaviors.

[3]SWIRL and TWIRL graphics were written in C by William Giarla. They were built upon graphics work previously developed at Rand for other projects.

III. CONCLUSIONS

The ROSS language represents our first attempt to develop a relatively complete modeling environment. Ideally, such an environment can help users understand, reason about, and even design a wide variety of complex entities. In this report, we have discussed how ROSS facilitates the construction and viewing of models, through object-oriented programming techniques, English-like language syntax, interactive debugging and editing tools, and textual and graphical output facilities. Much work remains. We are presently investigating the Time Warp mechanism (Jefferson and Sowizral, 1982), a methodology for speeding up simulations by distributing them. In addition, we wish to develop modeling capabilities that go beyond simulation. We view a simulation as one of several kinds of models. Although other approaches to modeling are less well developed (de Kleer and Brown, 1983), they deserve attention because simulation alone enables users to answer surprisingly few questions about the behavioral characteristics of their models (Davis et al., 1982). To improve modeling as a reasoning and design tool, we must not only make it easier for users to ask questions of their models, we must greatly extend the range of questions they can ask.

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