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Discrete-Event Simulation

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Abstract—This paper develops a message-based approach to discrete-event simulation. Although message-based simulations have the same expressive power as traditional discrete-event simulation languages, they provide a more natural environment for simulating distributed systems. In message-based simulations, a physical system is modeled by a set of message-communicating processes. The events in the system are modeled by message-communications. The paper proposes the entity construct to represent a message-communicating process operating in simulated time. A general wait until construct is used for process scheduling and message-communication. Based on these two notions, the paper proposes a language fragment comprising a small set of primitives. The language fragment can be implemented in any general-purpose, sequential programming language to construct a message-based simulator. We give an example of a message-based simulation language, called MAY, developed by implementing the language fragment in Fortran. MAY is in the public domain and is available on request.

Index Terms—Discrete-event simulation, distributed system, entity, message, message-based simulation.

I. INTRODUCTION

THIS paper has the following goals:
1) Develop a message-based approach to discrete-event simulation.
2) Show that a class of simulation languages may be obtained by adding a small programming language fragment to general-purpose, sequential programming languages like Fortran, Pascal, C, etc.
3) Give an example of a message-based simulation language, called MAY, derived from Fortran. MAY runs on a variety of machines including VAX® 11/780 (under UNIX®), DEC 20 (under TOPS-20), IBM 3033 (under VM) and the IBM PC (under MS DOS).

A large number of discrete-event simulation languages including GASP [16], SIMSCRIPT [9], SIMULA [4], and GPSS [17] are currently available. Although message-passing can be simulated in these languages, none of them provide it as a basic language construct. Some recent research efforts have been directed towards designing simulation systems around message-based programming languages. Two efforts in this direction are the design of SAMOA [12], a discrete-event simulation package built upon Ada® [1], and a simulation system designed by Kaubisch and Hoare [8] built upon CSP [6]. This paper develops a class of message-based simulation languages by enhancing sequential programming languages with a small number of message-passing and process-representation primitives. We describe a small programming language fragment which can be implemented within the framework of any existing sequential language to construct a message-based simulator. The few primitives required for message-based simulations are constructs to:
1) create and terminate processes;
2) send messages to processes;
3) wait for messages and/or simulation time to elapse.

What is the advantage of simulations in which events are message-communications? Message-based simulations do not provide additional expressive power. Indeed there are systems for which the constructs of standard simulation languages such as GPSS are more natural than those of message-based simulation. However, for simulating distributed systems, message-based simulations appear to be more natural. A simulation program written in a traditional simulation language like GPSS is inherently a sequential program and is developed using the constructs of sequential programming. A message-based simulation, on the other hand, "looks" like a distributed program. It is natural to develop a message-based simulation of a message-based distributed system.

The rest of the paper is organized as follows. Section II presents an informal description of message-based simulation. Section III explains the philosophy and design details of the constructs proposed in this paper. Section IV describes the language fragment that needs to be added to general-purpose programming languages to obtain message-based simulation languages. Section V gives a description of MAY, a message-based simulation language derived from Fortran. Section VI presents a few example programs coded in MAY. Section VII discusses implementation issues. Section VIII is the conclusion.

II. MESSAGE-BASED SIMULATION

This section presents an informal discussion of message-based simulation. In this paper we adopt the process view of simulation: a system being simulated is assumed to consist of a number of physical processes which inter-
act at discrete instants of time. The process interactions are called events and the time instants at which they occur, event times. Each physical process of the system is simulated by a logical process. As an example, consider the simulation of a doctor's office to determine the waiting time distribution of patients visiting the office. In the actual system, patients enter the office and wait in a queue to meet the receptionist. The receptionist fills out a medical form for the patient, who then waits to consult with the doctor. In the simulation, the doctor, receptionist, and patients are simulated by logical processes. Examples of events in this system are a patient entering a queue to talk to the receptionist and a patient completing his consultation with the doctor. Hereafter, we shall use terms like the patient process to refer to the logical process that simulates a physical patient process.

In message-based simulations, an event is the communication of a message. In the above example, the event of a patient entering the receptionist's queue may be simulated by a message being sent by the patient process to the receptionist process (and the associated queue); this message requests service from the receptionist process and is referred to as a message of type request, or simply as a request message. After sending the request message, the patient process waits to receive a reply message from the receptionist process. The reply message simulates the event of a patient having received his form from the receptionist. Internal actions of a physical process, i.e., actions that do not involve interactions with other processes in the system, are modeled either by the passage of simulation time or by the execution of sequential statements within the corresponding logical process.

We use a simulator clock to represent the passage of time in a simulation. The simulator clock advances in discrete steps, where each step simulates the passage of time between two events in the system. In message-based simulations, a process may wait until some time \( t \) specified by the process to receive a specific type(s) of message. While it is waiting for a specific message, other messages received by the process are enqueued in a message buffer associated with the process. The process may accept messages from its input buffer at a later point in the simulation, as explained subsequently. In our example, a patient entering the doctor's office may be willing to wait for up to 5 minutes to receive his form from the receptionist; if it takes any longer, the patient goes elsewhere. This can be simulated by the patient process waiting for up to 5 minutes of simulated time to receive the reply message from the receptionist process; if it takes any longer, the patient process simulates the departure of the patient from the system. A process waits for the passage of simulation time and/or to receive a specific type(s) of message by executing a wait statement, which has the form

\[
\text{wait } t \text{ for } b
\]

where \( t \) represents an integer-valued expression and \( b \) a Boolean condition. The condition \( b \) is used to specify the messages that the process is ready to accept and \( t \) specifies the maximum time up to which the process is willing to wait for the message(s). The process ceases to wait either when the simulator clock reaches the value represented by \( t \) or if it is receives a message that satisfies the condition \( b \), whichever occurs first. In our example, the receptionist may be at lunch, during which time he is willing to talk only to patients with an emergency; patients not having an emergency have to wait until the receptionist finishes his lunch. The event of a patient requesting emergency service from the receptionist is simulated by an emergency message being sent by the patient process to the receptionist process. The lunch-break of the receptionist may be simulated by executing the following wait statement:

\[
\text{wait } t_1 \text{ for (message-type = emergency)}
\]

where \( t_1 \) represents the time at which the receptionist finishes his lunch-break; the keyword message-type is used by a process to refer to the type of message received by it. Request messages received by the receptionist process while it is willing to accept only emergency messages are enqueued in the message buffer associated with the receptionist process. If an emergency message is received by the receptionist process, it ceases to wait and executes the next statement in its code. If the simulator clock moves forward to \( t_1 \) and the receptionist process has not received a message of type emergency, then the process is said to have timed-out. The timing-out of a process is simulated by the process receiving a special message, called a timeout message, from the simulation monitor. Reception of a time-out message by a waiting process forces it to cease waiting.

On ceasing to wait, a process proceeds to the next statement in its code. For instance, on ceasing to wait, a process may execute a statement of the form

\[
\text{if message-type = emergency then do x}
\]

else if message-type = time-out then do y
else do z.

The purpose of this informal discussion was to give the reader who is unfamiliar with message-based simulation a flavor of the technique.

III. Design Philosophy

This section contrasts the message-based approach to simulation with the approach adopted by some of the traditional discrete-event simulation languages.

Resources and processes are the two basic building-blocks of a simulation program. A resource is a passive object and may be represented by a simple variable or a complex data structure. A process on the other hand, is an independent, dynamic entity. Processes interact with each other and "use" the resources to achieve some objective. For instance, in the doctor's office example, the doctor and receptionist are resources that are used by the patient processes. A simulation program models the dynamic behavior of processes, resources, and their interactions as they evolve in time.
Most simulation languages treat resources and processes as two distinct concepts and provide separate primitives to model their behavior. Thus GPSS provides the built-in storage and transaction primitives, and SIMONE [7] the monitor and process primitives for this purpose. SIMULA uses the class concept to model resources, and a special subclass called the process class to model processes. However, as observed by Kaubisch and Hoare [8], the process and resource concepts are relative rather than absolute:

"...the processes and resources of a simulation algorithm display a multilevel tree organization (with the resources at the bottom and intermediate levels, and the pure processes at the top level). Looking from the top down, every structure looks like a resource; looking from the bottom upward, they look like processes. Even the processes at the top level would look like resources if we were to add another level to the tree..."'

The language fragment proposed in this paper uses a single program module, called an entity, to simulate both processes and resources. An entity is a sequential program module implemented in the host language with the following additional features: an entity may
1) create other entities;
2) terminate itself;
3) send messages to other entities; and
4) wait for the passage of time and/or receipt of messages.

The entity construct is a versatile modeling tool. It can be used to model a variety of different objects including abstract data types, recursive procedures, monitors, coroutines, processes, and resources. An entity-type models a class of objects. An instance of an entity-type represents a specific object of its class. Hereafter, we shall use the term entity to mean an instance of an entity-type. Each entity in the simulation has an independent data-space and its attributes cannot be accessed directly by other entities in the simulation.

Two primary operations are defined on an entity: creation and termination. The create primitive provided by our language fragment is semantically very similar to the new primitive provided in SIMULA. It allows multiple, independent instances of an entity-type to be created dynamically. An entity may also recursively create its own instances. Initially, every simulation consists of a single entity called main. Entity main does not model any real physical process; rather its purpose is to initiate and terminate the simulation.

Once created, an entity participates in the simulation until it ceases to exist. In SIMULA, if no references to an object exist, the object ceases to exist. Thus, a SIMULA object can be destroyed unconditionally by other objects in the simulation. The terminate mechanism proposed by our language fragment is different. The only mechanism by which an entity may terminate itself, is by executing the end-entity statement in its definition (see Section IV-C). An entity cannot be terminated by another entity in the system. On the basis of this design principle, even if no external references to an entity exist, the entity does not cease to exist. Attempts to refer to terminated entities result in error.

In a physical system, each process makes independent progress in time and many processes execute in parallel. In its simulation, the multiple processes of a physical system must be executed "simultaneously" on one processor. This simultaneity is achieved by interleaving the execution of different processes and executing them in a quasi-parallel fashion [5]. Quasi-parallel processing uses a time-measure that is distinct from real time. We refer to this as simulated time and the clock used to measure simulated time as the simulation clock. In a physical system, processes perform different tasks, each of which takes a certain amount of real time. In the simulation, this is represented by the process initiating the task and then being idle for the duration (as measured by the simulation clock) of the task completion. Scheduling primitives, provided by a simulation language, are used by a process to schedule its operations in simulated time. For instance, SIMULA provides a built-in procedure, hold, to allow a process to suspend its execution for a predetermined time duration. In our doctor's office example, we assume that the doctor takes 10 minutes to consult with a patient. In SIMULA, the class modeling a patient would contain the procedure call, hold(10) to represent this activity. The effect of executing the above statement would be to cause the process to wait for 10 units of simulation time to elapse. From the perspective of the patient process, if the value of the simulation clock was T before executing the procedure call, it would be T+10 after the call. However, the hold primitive is not sufficient to represent an activity that takes an unspecifiable amount of time. Thus, in the above example, when a patient enters the receptionist's queue, he cannot predict the amount of time he would have to wait before seeing the receptionist. To represent such activities, SIMULA provides the passive statement, which when executed by a process causes it to enter an idle state; the process remains in the idle state until it is explicitly activated by another process.

The wait-until primitive is a general-purpose scheduling primitive which allows a process to wait until an arbitrary condition is satisfied. This primitive was first introduced in the language SOL [10], in the following form:

\[ \text{wait-until (condition)} \]

where condition is a Boolean expression of arbitrary complexity. The hold primitive discussed earlier, can be expressed as a special form of the wait-until construct. For instance, hold(10) may be expressed as follows:

\[ \text{wait-until (time = current-time + 10)} \]

where time refers to simulated time. In addition, this primitive can be used to simulate a variety of other situations. For instance, in the doctor's office example, the activity of a patient waiting in the receptionist's queue
could be simulated by the patient process by executing the following statement

\[
\text{wait-until (removed-from-queue)}
\]

where \textit{removed-from-queue} is a Boolean variable that is set to \textit{true} by the receptionist process when the patient process has received the desired service.

The language fragment proposed in this paper uses a modified version of the \textit{wait-until} construct, called the \textit{wait} statement, which was introduced in Section II. In message-based simulation, an entity is in one of two states: \textit{active}, if it is currently executing, or \textit{waiting}, if it is not active. An \textit{active} entity moves to the \textit{wait} state by executing a \textit{wait} statement. Every \textit{waiting} entity has a \textit{wait-time} and a Boolean predicate, called the \textit{wait-condition}, associated with its \textit{wait} state. The \textit{wait-time} represents the maximum time that the entity can remain in the \textit{wait} state. An entity in the \textit{wait} state moves to the \textit{active} state either when it receives a message that satisfies its \textit{wait-condition} or if its \textit{wait-time} has expired. We define a special message, called a \textit{time-out} message, which is sent by the simulation monitor to a \textit{waiting} entity, when its \textit{wait-time} has expired.

The \textit{wait} statement is used both as a scheduling primitive as well as a \textit{receive} primitive for message-communications. Our communication protocol is based on buffered message-passing: execution of the \textit{send} primitive causes a message to be deposited in a FIFO manner in the message buffer associated with the recipient entity. We now describe the \textit{wait} statement in more detail: if an entity executes a \textit{wait} statement at simulation time \( T \) (i.e., when the simulator clock time is \( T \)) and the \textit{wait} statement is of the form

\[
\text{wait } T' \text{ for (message-type } = M)\]

where \( T' \) represents a time value such that \( T' \geq T \), the meaning of the \textit{wait} statement is as follows:

- The entity will cease waiting at time \( t, T' > t \geq T \), if a message of type \( M \) is received by the entity at time \( t \). In particular, if messages of type \( M \) are present in the message buffer of the entity at time \( T \), the entity receives the first message of type \( M \) from the buffer and ceases to wait at \( T \).
- The entity will cease waiting at time \( T' \), if no message of type \( M \) is received by it in the interval \([T, T')\). In this case, a \textit{time-out} message is received by the entity at \( T' \).

We note that if a message of type \( M \) is sent to the entity at time \( T' \), then the entity may first receive either the \textit{time-out} message or the message of type \( M \).

In message-based simulations, the communication of a message takes zero units of simulation time. For instance, in our doctor’s office example, we assume that the time taken by a patient to walk from the receptionist’s desk to the doctor’s cabin is insignificant; thus, in the simulation, the transmission time for the message that models this event is zero. Nonzero transmission delays in physical systems can be modeled by causing the process sending (receiving) a message to wait for a certain time corresponding to the message-transmission time before (after) sending (receiving) the message. Alternatively, the communication medium may be modeled as a separate process which incorporates the transmission delay.

Many simulation languages, for instance GPSS, provide built-in language primitives for statistics collection, queue representation, and random number generation. Our language fragment treats these facilities as “options” rather than “standard equipment.” As such, these facilities are provided to the programmer through a set of library entities and routines. An entity-type defined in the library, can be included in a user program by means of primitives provided by our language fragment. The library facility serves another useful purpose. A number of separate entities may be defined to model some primitive subsystems that comprise most distributed systems. Some examples of such subsystems are shared memory, ethernet, token-ring, processor, FIFO server, and priority server. Each of these subsystems may be programmed as an entity-type and stored in the library. The library can then serve as a tool-box to study the performance of various alternative configurations of a proposed distributed system.

IV. Constructs for Message-Based Simulation

In this section we present the message and process constructs provided by our language fragment. The programming language in which these constructs are to be embedded (e.g., Fortran, Pascal, Algol, C, etc.) is called the host language. This discussion ignores anomalies that may arise in the implementation of these constructs in a specific host language. For instance, we have assumed that processes communicate exclusively through messages. However, in a Pascal implementation, processes may also share information by means of global variables; or in a Fortran implementation, through common blocks. We assume that specific implementations will handle such anomalies on an individual basis. Further, the discussion in this section ignores all syntactic issues. The next section, however, gives a description of the Fortran implementation of these constructs.

A. Entities

An entity-type models objects of a given type. The declaration of an entity-type is similar to that of a procedure or subroutine in the host language. An entity-type consists of an entity heading, a local variable declaration section, a message declaration section, and an entity body. The entity heading declares the name and formal parameters of the entity-type in a manner similar to the declaration of a procedure heading in the host language. An entity-type, however, is only allowed to have input parameters. The local variable section is identical to that of a procedure. The message declaration section is used to declare the various types of messages that may be received by all instances of this entity-type. A message declaration con-
sists of the string **message** followed by a name and a parameter list. The structure of the parameter list is similar to that of a formal parameter list in the host language. The entity body consists of sequential statements of the host language (e.g., assignment statement, procedure call, etc.) with the following additional statements:

- **let** statement: used to create new entities.
- **end-entity** statement: used by an entity to terminate itself.
- **invoke** statement: used to send messages to other entities.
- **wait** statement: used to wait for the passage of simulation time or to wait to receive messages.

We now describe the semantics of each of the above statement types.

**B. Let Statement**

We define a scalar variable type called **entity-identifier**. Every entity in the simulation is assigned a unique identification number which is stored in a variable of type **entity-identifier**. Variables of this type are used exclusively to store the identifier of entities and no arithmetic operations can be performed on them. An entity is created by the execution of a **let** statement which has the following form:

```plaintext
let e1 be entity-type-name(actual parameter list)
```

where **e1** is a scalar variable of type **entity-identifier**.

Execution of the above statement causes a new instance of the specified entity-type to be created; the identifier of the newly created entity is stored in **e1**. The formal parameters of the entity-type declaration are bound to the actual parameters in the **let** statement, as in the manner of a procedure call, at the point that the entity is created. The identifier **e1** may be used to send messages to the entity. Every entity-type declaration contains a predefined local variable, called **myid**, which is of type **entity-identifier**. When a new entity is created, its identifier is automatically stored in its **myid**.

**C. End-entity Statement**

The **end-entity** statement is an executable statement, which when executed causes the entity to terminate. The statement has the form:

```plaintext
end-entity
```

An entity can only terminate by executing the **end-entity** statement in its entity definition. The entity is said to exist between the point that it is created to the point that it terminates itself. Attempts to refer to nonexistent entities result in error.

**D. Invoke Statement**

Messages are sent by one entity to another using an **invoke** statement which has the following form:

```plaintext
invoke e1 with m1(actual-parameter-list)
```

**e1** must be of type **entity-identifier**. Execution of the above statement results in a message of type **m1** being sent to the entity **e1** provided:

- **entity e1** exists.
- a message with name **m1** has been declared in the message receive section of the entity-type declaration of entity **e1**.
- the types of the formal and actual parameters of message **m1** match.

An attempt is made to deliver the message at the current value of the simulation clock. However, if the recipient entity **small-list** to represent a small list of integers. This message is stored in a buffer associated with the recipient entity and may be accepted by it subsequently (see discussion under **wait** statement).

**E. Wait Statement**

The **wait** statement is used by an entity to wait for the passage of simulation time and/or to receive messages. The statement has the following form:

```plaintext
wait t for b
```

where **t** is an integer-valued expression denoting time; and **b** is a Boolean condition of arbitrary complexity. This statement has been discussed extensively in the previous sections. In this section, we present a few examples of the more frequently used instances of this statement.

If the condition **b** is the Boolean constant **false**, the entity ceases to wait only when the simulation time reaches the time value specified in the wait statement. For instance, execution of the statement

```plaintext
wait t for false
```

will cause the entity to wait until the simulation time is **t**; all messages sent to it in the interim will be stored in its message buffer. In contrast, the condition **b** may be the Boolean constant **true**, as in the following statement:

```plaintext
wait t for true
```

If the message buffer of the entity is nonempty when the above statement is executed, the first message is removed from the buffer and delivered to the entity causing it to resume execution at the current value of the simulation clock. However, if the message buffer is empty, the entity will wait to receive a message. If no messages are received by the entity, and the simulation time reaches **t** units, a **time-out** message is sent to it at simulation time **t**, to force it to cease waiting.

The time part of the wait statement may be omitted. In this case, the **wait-time** associated with the entity is assumed to be infinity (represented by an arbitrarily large positive integer). In our doctor's office example, while the doctor is not busy, he sits in his office waiting for the next patient to arrive (we assume that the doctor never quits working!). The **doctor** entity would then contain a wait statement of the form

```plaintext
wait for (message-type = request)
```
F. Examples

This section illustrates how an entity may be used to model a variety of objects including abstract data types, monitors, coroutines, and recursive procedures. The section culminates in a complete example of a message-based simulation.

Abstract Data Types: An entity may be used to represent an abstract data type. Operations on the data type are performed by means of messages sent to the entity modeling the data type. As an example, we describe an entity small-list to represent a small list of integers. This example has been adapted from [6]. Two operations may be performed on this list: insert to insert an integer in the list; and belongs to check if a given integer belongs to the list. The insert operation may be performed by sending an insert message to the entity; to perform the belongs operation the user process sends a belongs message to the entity; the entity responds with a position message giving the position of the element in the list (it returns 0, if the element does not belong to the list).

entity small-list(list-size : integer);
{ Local Variable Declaration Section }
list-array:array[1..list-size] of integer;
pos,size : integer;
{ Message Receive Declaration Section }
message insert(element : integer);
message belongs(element : integer; sender-id : entity-identifier);
{ Entity Body }
size := 0;
while true do
begin
{ wait indefinitely to receive the next message }
wait for true;
{ the procedure search is used to locate the position, pos, of the element in the array; pos is set to 0 if the element is not present. }
search(list-array,size,element,pos);
if (message-type = insert) and (pos = 0) then
begin
if (size = list-size) then overflow-error
else begin
size := size + 1;
list-array[size] := element;
end
end
else if (message-type = belongs) then
invoke sender-id with position(pos);
end
end-entity;

Recursive Procedures: To illustrate how an entity may be used to model recursive procedures, we define an entity sieve which recursively sieves out all prime numbers from a sequence of consecutive natural numbers beginning with the smallest prime, 2. The entity sieve is defined with one parameter. Multiple instances of the sieve object are created recursively as needed. For instance, the ith sieve, say $s_i$, is created with the ith prime number, say $p_i$ as its parameter, by the $(i-1)$th sieve. Subsequently, $s_i$ sieves out all multiples of $p_i$ from the sequence of numbers passed to it by sieve $s_{i-1}$. The next prime number in the sequence, say $p_{i+1}$, is the smallest integer greater than $p_i$, which was not sieved out by sieves $s_1 \ldots s_{i-1}$. When $s_i$ receives this number, it creates the next sieve object, $s_{i+1}$ with $p_{i+1}$ as its parameter.

A driver entity is used to initiate the program. This entity creates the first sieve entity $s_1$ with the smallest prime, 2 as the actual parameter. It then passes consecutive natural numbers to $s_1$ via a stream of send messages. The code for the driver routine has been omitted for brevity.

entity sieve(prime: integer);
{ Local Variable Declaration Section }
next-sieve : entity-identifier;
{ Message Receive Declaration Section }
message send(number:integer);
{ Entity Body }
{ Wait to receive the next integer in the sequence }
wait for (message-type = send);
{ The first message received contains the next prime in the sequence. Create the next sieve process, using number as the parameter }
let next-sieve be sieve(number);
while true do
begin
wait for (message-type = send);
{ From the subsequent messages received, sieve out all multiples of prime and pass the rest to sieve next-sieve. }
if (mod(number,prime) < > 0) then
invoke next-sieve with send(number);
end;
end-entity;

Coroutines: Coroutines can be naturally modeled by entities. As an example, consider an unbuffered producer-consumer system. The producer process produces a value and sends it to the consumer process. In the absence of a buffer, the producer process must wait until the value has been accepted by the consumer process, before it can produce the next value. The two coroutine-like processes may be modeled by the producer and consumer entity-types, respectively.

entity producer;
{ Local Variable Declaration Section }
value : integer;
{ Message Receiver Declaration Section }
message more(consumer-id: entity-identifier);
if (message-type = send) then
begin
store((mod(in, buffer-length)) + 1) := value;
in := in + 1;
end
else if (message-type = more) then
begin
value := store((mod(out, buffer-length)) + 1);
out := out + 1;
invoke consumer with receive(value);
end
end;
end-entity;

entity buffer(buffer-length:integer);

{ Local Variable Declaration Section }
in, out : integer;
store:array[1..buffer-length] of integer;

{ Message Receive Declaration Section }
message send(value:integer);
message more(consumer:entity-identifier);

{ Entity Body }
{ initialize the buffer }
in:=0
out:=0
while true do
begin
if (in = out + buffer-length) then
wait for (message-type = more)
else if (in = out) then
wait for (message-type = send)
else wait for true;

Simulation Model of a Doctor’s Office: We develop a message-based simulation model of the doctor’s office described earlier. This is a complete simulation example which illustrates how processes may be modeled by entities. To summarize, in the physical system, patients enter the office through a door, meet the receptionist to obtain their forms, consult with the doctor and then exit from the office. The door may be modeled by a source entity which creates patient entities at a rate equal to the arrival rate of patients at the door. We represent the interarrival time between two patients by the variable next-arrival. The identifiers of the doctor and receptionist entities are passed to the patient entities as entity parameters. On being created, a patient entity requests service from the receptionist entity by sending it a request message, and waits to receive the reply message. On receiving the reply message from the receptionist, it requests service from the doctor entity by sending it a request message. It then waits indefinitely for the reply message which indicates the completion of the examination. On receiving this message, the patient entity terminates itself.

We model both the doctor and receptionist entities as instances of one entity-type, called server. The server entities are assumed to exist forever. When idle, they accept a request message sent to them, wait for a certain time corresponding to the service time of the request to elapse, and then wait for the next request. Request messages received by a server entity, while it is busy serving another request, are buffered; after the server entity finishes serving the current request, it accepts the first request message from the buffer.

The entity-type main initiates the simulation by creating the doctor, receptionist and source entities. The simulation is terminated when all entities have been terminated or when the value of the simulator clock exceeds the value of a keyword max-simulation-time. The keyword clock represents the current value of the simulator clock. The program representing the above simulation model is presented in Pascal-like pseudo-code in Fig. 1.

The next section presents a detailed description of a message-based language called MAY in which Fortran is the host language. This section may be skipped by those who want to have an understanding of how message-based languages may be developed from host languages but have less interest in details of a Fortran implementation.
entity main;
{ Local Variable Declaration Section }
door, doctor, receptionist : entity-identifier;
{ Message Receive Declaration Section }
{ Message type: time-out is implicitly defined for every entity and
must not be defined by the user. Since no other message types
are used by this entity, this section is empty }
message :
{ Entity Body }
read (form-fill-time, consult-time, next-arrival, sim-period);
let receptionist be server(form-fill-time);
let doctor be server(consult-time);
let door be server(next-arrival, receptionist, doctor);
max-simulation-time := sim-period;
wait (clock + sim-period) for false;
end-entity.

entity source(int-arrival : integer, server1, server2 : entity-identifier);
{ Local Variable Declaration Section }
next-patient : entity-identifier;
{ Message Receive Declaration Section }
message :
{ Entity Body }
while true do
begin
let next-patient be patient(server1, server2);
wait (clock + inter-arrival) for false;
end;
end-entity.

entity patient(reception, doc : entity-identifier);
{ Message Receive Declaration Section }
message reply;
{ Entity Body }
invoke reception with request(mid);
wait for (message-type = reply);
invoke doc with request(mid);
wait for (message-type = reply);
end-entity.

entity server(mean-service-time : integer);
{ Message Receive Declaration Section }
message request(patient-id : entity-identifier);
{ Entity Body }
while true do
begin
wait for (message-type = request);
wait (clock + mean-service-time) for false;
invoke patient-id with reply;
end;
end-entity.

Fig. 1. Message-based simulation model of a doctor’s office.

V. DESCRIPTION OF MAY

This section gives a concise definition of MAY, a message-
based simulation language implemented in Fortran.
A complete description of MAY is given in [13]. The syntax
of MAY statements is given in BNF using the following
meta-symbols:

- Represents alternatives; for instance a/b
  implies the presence of symbol a or sym-
  bol b in the corresponding statement.

{} Optional in the corresponding statement.

identifier Any Fortran identifier of type integer.

A. Entity Definition

A MAY entity has the following structure:

\[
\text{entity-definition} ::= \text{entity-definition} \{ \text{variable-declaration} \}
\]

\[
\text{message-declaration} \text{ entity-body}
\]

Entity Heading: The entity heading contains the name
of the entity-type and specifies the parameters that may
be needed for its definition. The parameters may be scalar
integer variables or one-dimensional array of integer
variables. A scalar variable may optionally be followed
by a size specification, which specifies the maximum per-
missible value for the corresponding actual parameter.
An array parameter may be dimensioned by a scalar param-
eter whose maximum size has been specified. The entity
heading has the following syntax:

\[
\text{entity-heading} ::= \text{entity} \text{ entity-name}
\{ \text{parameter-list} \}
\]

\[
\text{entity-name} ::= \text{identifier}
\]

\[
\text{parameter-list} ::= \text{parameter} \{ \text{parameter-list} \}
\]

\[
\text{parameter} ::= \text{identifier} \text{ identifier} \text{ positive}
\]

\[
\text{integer} ::= \text{identifier} \text{ identifier} \text{ positive}
\]

\[
\text{simple-par} ::= \text{identifier} \text{ identifier} \text{ positive}
\]

\[
\text{array-par} ::= \text{identifier} \text{ identifier} \text{ positive}
\]

As an example, consider the heading for an entity-type
histro, representing a histogram used to measure the fre-
cquency with which the value of a variable occurs within
different specified intervals. The parameters required to
represent a general histogram object may be:

\[
\text{ntrval} ::= \text{Number of intervals for the frequency dis-
tribution; we choose a maximum of 50
intervals.}
\]

\[
\text{minval} ::= \text{The minimum expected value for the var-
iable.}
\]

\[
\text{ntrarr[i]} ::= \text{the upper bound for the ith interval; } i =
1 \cdots \text{ntrval}.
\]

The heading would then be coded as:

\[
\text{entity histro(ntrval : 50, minval, ntrarr[ntrval])}
\]

Since the array ntrarr is dimensioned by ntrval, the size
of the actual array parameter cannot exceed 50. Para-

ters are treated as constants in the body.

Variable Declaration Section: The variable declara-
tions of an entity-type consist of Fortran declaration state-
ments and MAY local integer statements. The values of
variables declared as local integers are defined even when
the entity is waiting (i.e., not executing). MAY local
variables may be integer scalar variables or one-dimen-
sional arrays of integer variables. The local integer
statement has the following syntax:

\[
\text{variable-declaration} ::= \text{local integer} \text{ variable}
\]

\[
\text{variable} ::= \text{variable} \{ \text{variable} \}
\]

\[
\text{array-variable} ::= \text{identifier} \text{ identifier} \text{ positive}
\]

\[
\text{array-var} ::= \text{identifier} \text{ identifier} \text{ positive}
\]

integer

\[
\text{simple-var} ::= \text{identifier}
\]

\[
\text{simple-par} ::= \text{identifier} \text{ identifier} \text{ positive}
\]

\[
\text{array-par} ::= \text{identifier} \text{ identifier} \text{ positive}
\]

\[
\text{simple-par} ::= \text{identifier} \text{ identifier} \text{ positive}
\]

\[
\text{array-par} ::= \text{identifier} \text{ identifier} \text{ positive}
\]
The histo entity-type discussed above, may use the following local integers:

values: An array which stores the frequency of occurrence of the values of a variable in the different intervals.

total: Stores the total of all values.

values: Stores the total number of values in all intervals.

These are declared by the following MAY statement:

\textbf{local integer} values (ntrvl), total, novals

Message Declaration Section: This section declares the types of messages that may be received by entities of a given type. Each message declaration has the following syntax:

\[
\text{message-statement} ::= \text{message} \ [\text{message-name}] \ \\
\text{(parameter-list)}
\]

\[
\text{message-name} ::= \text{identifier}
\]

\[
\text{parameter-list} ::= \text{parameter}\{, \text{parameter-list}\} \ \\
\text{simple-par} ::= \text{identifier} | \text{array-par}
\]

\[
\text{array-par} ::= \text{identifier} \ [	ext{positive integer}]
\]

Messages contain only input parameters which may be scalars or variable length one-dimensional array variables. All message parameters must be of type integer. Two parameterless message types \textit{init} and \textit{tmout} are defined by the translator for every entity and must not be defined by the user.

\textit{init:} As soon as it is created, an entity is invoked with the \textit{init} message. The purpose of this message is to cause execution of the initializing statements in the entity description.

\textit{tmout:} An entity is invoked with a \textit{tmout} message when the simulation time reaches the value specified by the last \textit{wait} statement that was executed by the entity.

Consider the declaration of a message to be used to pass a set of values to an entity of type \textit{histo}.

\textbf{message insert(novals, values[20])}

The above declaration defines a message called \textit{insert} which has two parameters, the second parameter being an array of size 20. The corresponding actual parameter (in the \textit{invoke} statement) is expected to be an array. The array may be of any size, up to a maximum of 20.

Entity Body: The entity body consists of a set of executable Fortran and MAY statements which may include the \textit{let}, \textit{invoke}, and \textit{wait} statements. The last statement in the body of the entity definition must be the end-entity statement, which when executed causes the termination of the entity-instance (see discussion on entity termination below).

B. Entity Creation

An entity can create an instance of an entity-type by executing a \textit{let} statement which has the following syntax:

\[
\text{let-statement} ::= \text{let} \ \text{(entity-instance-name)} \ \text{be} \ \\
\text{(entity-name)} \ \{	ext{(actual-par-list)} \}
\]

\[
\text{(entity-instance-name)} ::= \text{identifier} \ | \text{subscripted identifier}
\]

\[
\text{(entity-name)} ::= \text{identifier}
\]

\[
\text{(actual-par-list)} ::= \text{parameter}\{, \text{actual-par-list}\} \ \\
\text{parameter} ::= \text{identifier} \ | \text{subscripted identifier} \ | \text{array name [integer]}
\]

The identifier of the created entity is stored in the variable represented by \textit{(entity-instance-name)}. The type \textit{entity-identifier} is implemented in MAY as an integer type.

Consider the creation of an instance of entity \textit{histo} with the following attributes:

- Number of intervals = \textit{num}.
- Minimum value = \textit{min}.
- Upper bound for the \textit{i}-th interval (\textit{i}: 1 \ldots 20) = \textit{bounds}(\textit{i})

where \textit{bounds} is an array variable whose dimension is 20.

An instance of the \textit{histo} entity with the above attribute values is created by the following \textit{let} statement:

\[
\text{let hist1 be histo(num, min, bounds)}
\]

where \textit{hist1} has been declared as a local variable of type integer in the creator module. The identifier of this entity is stored in variable \textit{hist1}.

C. Entity Termination

An entity terminates itself by executing an end-entity statement which has the following syntax:

\[
\text{end-entity-statement} ::= \text{ende}
\]

D. Invoke Statement

A message may be sent to an entity by means of an \textit{invoke} statement which has the following syntax:

\[
\text{invoke-statement} ::= \text{invoke} \ \text{(entity-instance-name)} \ \\
\text{with} \ \text{(message-name)} \ \\
\text{(parameter-list)}
\]

\[
\text{(entity-instance-name)} ::= \text{identifier} \ | \text{subscripted identifier}
\]

\[
\text{(message-name)} ::= \text{identifier}
\]

\[
\text{(parameter-list)} ::= \text{parameter}\{, \text{parameter-list}\} \ \\
\text{parameter} ::= \text{identifier} \ | \text{subscripted identifier} \ | \text{array par}
\]

\[
\text{array par} ::= \text{identifier}[\text{identifier} \ | \text{positive integer}]
\]
A message of type insert may be passed to the entity hist1 (if it exists), by executing the following statement:

\texttt{invoke hist1 with insert(5, values[5])}

The message has two parameters, the second being an array of 5 elements.

\textbf{E. Wait Statement}

The wait statement has the following syntax:

\[
\text{\langle wait-statement\rangle} \ ::= \ \text{wait} \ \{ \ \langle t \rangle \ \} \ \{ \ \text{for} \ \langle b \rangle \ \}
\]

\[
\langle t \rangle \ ::= \ \text{FORTRAN} \ \text{integer arithmetic expression}
\]

\[
\langle b \rangle \ ::= \ \text{FORTRAN} \ \text{boolean condition}
\]

If the \texttt{for} part of the wait statement is omitted, the condition \texttt{\langle b \rangle} is assumed to be the Boolean constant \texttt{true}. If the time-part of the wait statement is omitted, the variable \texttt{\langle t \rangle} is assumed to the \texttt{maxint}, an arbitrarily large number.

\textbf{F. Append Statement}

The entity-types defined in the MAY library can be included in MAY programs by means of an append statement. A library entity may be used as any of the other entities defined in the program. An append statement has the following syntax:

\[
\text{\langle append-statement\rangle} \ ::= \ \text{append} \ \{ \ \langle entity-name-list\rangle \ \}
\]

\[
\langle entity-name-list\rangle \ ::= \ \langle entity-name \rangle \\}
\]

\[
\langle entity-name\rangle \ ::= \ \text{identifier}
\]

\textbf{VI. MAY Examples}

We now present a few modeling and simulation examples coded in MAY.

\textbf{A. Representation of Processor Configurations}

A variety of processor configurations can be represented in MAY. We present a few examples illustrating how processors interconnected in a pipeline, organized as a hierarchy, or connected in a two-dimensional mesh can be modeled in MAY.

A pipeline of \(n\) processors may be created by executing the following code segment:

\[
\text{do } 10 \ i = 1, n \\
\text{let pipe(i) be processor} \\
10 \ \text{continue}
\]

However, processor pipe\((i)\) cannot communicate with pipe\((i + 1)\) unless it knows its identity. There are several ways in which a processor may obtain the identity of its neighbor: after all processors have been created, a message may be sent to each processor giving it the identity of its neighbor; alternatively, every processor (except the last one in the pipeline) may be given the identity of the next processor in the pipeline as an entity parameter. This is achieved by executing the code segment shown below:

\[
\text{let pipe(n) be processor(0)} \\
\text{do } 10 \ i = n - 1, 1, -1 \\
\text{let pipe(i) be processor(pipe(i + 1))} \\
10 \ \text{continue}
\]

A binary tree of \(2n + 1\) processors, where \(n\) is a positive integer, may be created by executing the following statements. The processors form a complete binary tree in that all leaf nodes occur at the same level in the tree.

\[
\text{let node(1) be processor(0)} \\
\text{do } 10 \ i = 1, n \\
\text{let node(2i) be processor(node(i))} \\
\text{let node(2i+1) be processor(node(i))} \\
10 \ \text{continue}
\]

In the above example, each node knows the identity of its parent. To permit a node to communicate with its child nodes, each node (except the root node) may send its identity to its parent node in a message.

As another example, consider a mesh of \(n^2 + 2n\) processors, in which each of the processors represented by processor\((i, j)\); \text{\texttt{i: 1 \cdot n, j: 1 \cdot n}}, communicates with processor\((i + 1, j)\) and processor\((i, j + 1)\). Processors\((i, n + 1); \text{\texttt{i: 1 \cdot n, and processors(n + 1, j); j: 1 \cdot n}}, are sink processors. This configuration may be used to implement a fast parallel algorithm to compute the product of two matrices [6]. The above configuration may be created by the following code segment:

\[
\text{C create the sink processors.} \\
\text{do } 10 \ i = 1, n \\
\text{let mesh(i, n + 1) be processor(0, 0)} \\
\text{let mesh(n + 1, i) be processor(0, 0)} \\
10 \ \text{continue}
\]

\[
\text{do } 20 \ i = n, 1, -1 \\
\text{do } 20 \ j = n, 1, -1 \\
\text{let mesh(i, j) be processor(mesh(i, j+1), mesh(i+1,j))} \\
20 \ \text{continue}
\]

\textbf{B. Simulation of a Doctor’s Office}

This program illustrates the simulation of the doctor’s office example introduced earlier in the paper. The program is a refinement of the pseudo-code developed in Section IV-F. The doctor’s office is modeled as a simple queuing network with a source entity simulating the door and two server entities which simulate the receptionist and doctor, respectively. In addition to the entities discussed earlier, the program uses a MAY library entity-type called histo. An instance of the histo entity-type is used in the program to generate a frequency distribution of the total time spent by patients in the system.

A MAY program consists of a collection of user-defined entities, library entities and Fortran subroutines, with no “main program” segment. However, every MAY program must define a parameterless entity called main. This entity is used to initiate the MAY simulation. The simulation is normally terminated when all entities have
been terminated. It is terminated before this point if the value of the simulator clock, represented by clock is greater than the value of a MAY keyword izstim. The variable izstim may be assigned an integer value within any entity in the MAY program. The keyword maxint represents an arbitrarily large integer. The keyword msg is used by an entity to refer to the type of the last message received by it. The complete code for the program is given in Fig. 2.

VII. IMPLEMENTATION ISSUES

Message-based simulation languages may be developed by implementing the language fragment described in this paper in any sequential programming language. Two simulation languages, MAY [3] based on Fortran, and SOF [15] based on Pascal, have been implemented at the University of Texas at Austin. A preprocessor is used to translate programs written in the simulation language (e.g., MAY) into the corresponding host language (e.g., Fortran). The output from the preprocessor is compiled using a standard host language compiler (e.g., f77 under UNIX). A specific preprocessor can be implemented very rapidly. The MAY preprocessor, which was written in Fortran, took less than two man-months to implement. Since the MAY statements constitute a small percentage of the simulation program, the overhead associated with the translation is low. The preprocessor contains extensive error detection facilities. In particular, syntactic checks are provided to ensure that all message-types and entity-types referred to in the program have been defined. In addition, code is generated to check for run-time errors like references to terminated entities, exceeding the specified maximum size of a formal entity parameter, etc.

The implementation provides a trace facility which can be used to trace the various messages received by an entity and/or print the state of an entity at various points in the simulation. Using this facility, it is possible to dynamically trace the execution of specific entities or all entities.

---

Fig. 2. MAY program to simulate a doctor’s office.
of a given entity. The tracing may be performed at different levels depending to the detail to which the state information of an entity is desired. Further, an entity may be traced over specific time period, or tracing initiated on a certain condition corresponding to a possible error in the program.

VIII. Conclusion

This paper developed a message-based approach to discrete-event simulation. Message-based simulators are a natural way to model distributed systems. The paper described how a class of message-based simulation languages could be developed by enhancing general-purpose sequential languages with a few message-passing and process representation constructs. The features needed for message-based simulation were illustrated by means of a Fortran derived message-based simulation language, called MAY. The language developed is simple, easy to learn and portable. It is currently being used to study the performance of distributed simulation techniques [11], performance of various distributed algorithms [2], and for the modeling and simulation of certain distributed systems [14].

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References


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