digital computer simulation

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HAYDEN BOOK COMPANY, INC.
Rochelle Park, New Jersey

To
KAREN
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Library of Congress Cataloging in Publication Data

Maryanski, Fred.
Digital computer simulation.

Includes bibliographical references and index.
1. Digital computer simulation. I. Title.
QA76.9.C65M37 001.4'24 80-10675
ISBN 0-8104-5118-2

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Printed in the United States of America

1	2	3	4	5	6	7	8	9	PRINTING
80	81	82	83	84	85	86	87	88	YEAR

Preface

One of the most widespread scientific applications of computers is the modeling of systems.

Programs are developed to simulate space flights, manufacturing processes, war games, biological structures, the potential effects of economic policy, and a myriad of other situations. Decisions based upon these computer models have a major impact upon our everyday lives. This book provides an introduction to the subject of simulation.

The emphasis is upon supplying the reader with sufficient background to perform a complete simulation experiment. All aspects of a simulation study are treated including specification, design, coding, debugging, analysis, validation, and interpretation. Four simulation programming languages, GPSS, SIMSCRIPT, CSMP, and DYNAMO, are presented with detailed examples and exercises. A presentation of the basic notions of probability and statistics is included to aid the reader in the analysis and understanding of simulation results. In the final chapter, the applications and limitations of simulation are discussed so that the reader can properly evaluate the impact of a simulation study.

The book is structured so that a complete simulation experiment can be carried out by a reader whose only prior experience is programming in a high-level language. Each simulation programming language chapter contains a single example which grows as new features of the language are introduced. Sample listings and output from actual runs are provided with each example. Tested exercises are provided after each chapter.

The book can serve as a text for a first course in simulation at the junior, senior, or first year graduate level in a computer science, industrial engineering, electrical engineering, or business administration department. Prior high-level language programming language and a limited amount of mathematical sophistication is assumed. People in industry with the need to design, develop, manage, or commission a simulation study will find the material helpful.

The text begins with a discussion of the basic concepts of system modeling and simulation in Chapter 1. Attention is then focused on the modeling of discrete systems for the next three chapters. In Chapter 2, the basic problems of discrete system simulation are presented along with some elementary queuing concepts. Chapter 3 is devoted to the GPSS simulation programming language, while SIMSCRIPT is the subject of Chapter 4. The next two chapters are the most mathematically oriented. Chapter 5 presents basic concepts of probability and statistics useful to the modeler. The sixth chapter focuses upon the design and analysis of simulation experiments, discussing common errors and validation techniques. In Chapter 7 the emphasis switches to continuous systems with the presentation of the CSMP programming language. The following chapter details the DYNAMO language and the Systems Dynamics approach to simulation. The concluding chapter discusses the value of simulation so that the reader may form a perspective on the applicability of simulation to a particular discipline.

I would like to thank Dianne Littwin for her encouragement and support in the development of this book. The helpful comments and insights of Michael Marcotty of General Motors Research Institute are appreciated. Madi McArthur is to be thanked for her heroic efforts in transcribing my unusual script into a readable manuscript. My final thanks go to the students in CS710 at Kansas State University from 1975 to 1978 who served as a test population and provided many helpful suggestions.

Fred Maryanski

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1 System Modeling and Simulation

1.1 SYSTEM MODELS

The purpose of this text is to present methods for using digital computers to perform system simulation studies. The word *system* is perhaps redundant since every simulation by definition characterizes the behavior of some type of system. System here means any orderly collection of objects. The simulation studies are specialized to describe computer systems, biological systems, economic systems, and so forth. Rather than concentrate on any one area, this section emphasizes general properties of systems that are significant in digital computer simulations.

The initial step in a simulation study is the development of a system model. A system is composed of objects, called *entities,* that have properties or attributes. One of the key operations in developing the system model is *abstraction.* Abstraction entails eliminating all but the significant attributes from the entities in the system. For example, consider a simulation study made by a bank to determine the best organization for its teller stations. Table 1.1 shows the entities and a list of possible attributes of this system. If the goal of our simulation study is to configure the teller waiting lines in a manner that minimizes customer waiting time and maximizes the service time of tellers, then many of the attributes of Table 1.1 can be removed from the model. In fact, a useful model of this system can be derived with only one attribute per entity (i.e., Transaction Processing Rate for the Teller and Number of Transactions for the Customer).

Simulation models describe changes in a system. Processes that cause system changes are called *activities*. The *state* of a system is a description of all entities, attributes, and activities at any given time. The concept of system state is somewhat abstract. Most systems have a very large number of possible states. It is the purpose of simulation models to describe changes in the system state. If a system reaches a state from which no change is possible, it is said to be in a *steady* state. States that are not steady are known as *transient* states.

In our bank teller model, the activities include a customer entering the bank, a customer selecting a line, a teller processing the customer's transactions, and a customer leaving the bank. The state of the bank could be described by the number of active tellers, the number of customers in each waiting line, the amount of time spent waiting by each customer, the number of transactions per customer, and the percentage of idle time by each teller. It is likely that the bank will reach a steady state only if the simulation continues until the end of the banking day. Then the state with all lines empty and all tellers idle is a steady state. All of the intermediate states passed through from the beginning of the simulation until the close of banking are transient states.

Each system resides in an environment. For purposes of a simulation, the interaction between the system and its environment must be clearly defined. Activities whose effects remain wholly within the system are termed *endogenous*. *Exogenous* activities are those in the environment that affect the system. Systems can be classified by the type of activities that they contain. Systems with exogenous activity are considered to be *open*. A system with strictly endogenous activity is *closed*.

For example, a simulation model of the growth of a cell is a closed system. However, the bank model previously described is an open system since the activities of customer arrival and departure affect the bank's immediate environment as well as the bank.

A means of classifying system behavior that has a substantial bearing on the type of simulation model for the system is based on the certainty of reaching a given state from the current state. If for a given initial state the sequence of inputs uniquely determines the sequence of states that the system attains, the system is said to be *deterministic*. If for a given initial state and input sequence the behavior of the system varies randomly, the system is *stochastic*.

An example of a deterministic model can be found in a simulation of electronic circuits—that is, digital computer components. Provided that the cir-

Table 1.1 Entities and Attributes

Entity	*Teller*	*Customer*
A	Height	Account No.
t	Weight	Age
t	Hair Color	Eye Color
r	Name	Number of Transactions
i	Social Security No.	Marital Status
b	Transaction Processing Rate	Education
u	Years of Service	Number of Accounts
t	Salary	Net Worth
e	Unused Vacation Time	Political Party
s	Favorite Color	Sign of Zodiac

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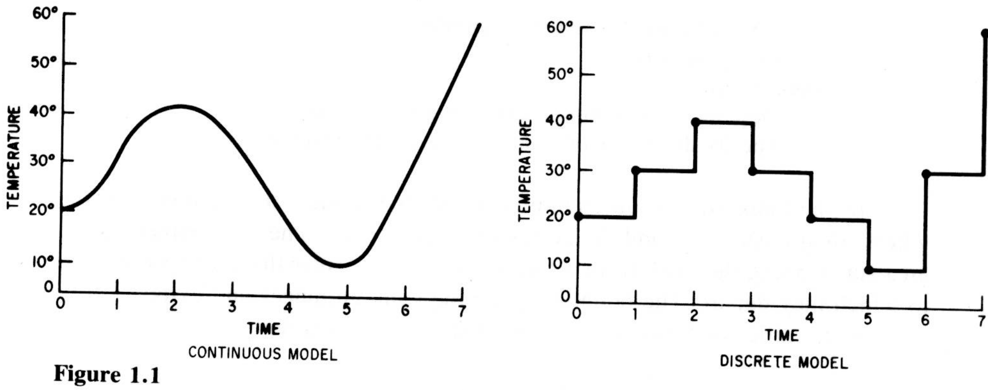

Figure 1.1

cuit has no faults, for a particular set of input signals a unique set of output signals will result.

This model becomes stochastic if we associate a failure probability with each component in the system. In this situation the output signals will have a random distribution due to the possibility of hardware failures.

Virtually all the simulation techniques presented in this text are for stochastic system models. The reason for conducting a simulation study is to gain information about a system that cannot be obtained through observation or analysis. Systems with random behavior or driven by random inputs are particularly difficult to analyze. Consequently, stochastic simulation methods are an important tool for studying many systems.

There are two basic techniques for modeling stochastic systems. A *discrete* system model allows changes at fixed time intervals. A discrete model in essence provides a series of snapshots of the system state. The alternative approach is *continuous* system modeling, in which system behavior is described as a continuous function from the beginning to the termination of the simulation. In general, the output of a discrete system simulation is a set of points, while a continuous simulation will produce a smooth curve. Figure 1.1 illustrates the basic difference between discrete and continuous functions.

1.2 SYSTEM MODELING

The previous section established the terminology of system models. In this section the important aspects of creating system models for digital simulations are presented. System modeling can be considered as a two-step process.

Steps in System Model Synthesis

1. Structural modeling
   a. Define boundaries between system and environment
   b. Identify entities

   c. Abstract critical attributes of entities
   d. Define activities
2. Data modeling
   a. Describe relationship of activities and attributes
   b. Specify the means of obtaining values for the attributes

In the bank simulation example, the system under study consists of the tellers, their customers, and the customer waiting lines. The environment is the area surrounding the bank from which the customers enter the waiting lines and to which they depart. The boundaries are the bank entrances and exits.

The entities and their associated attributes are as follows:

1. Customers—number of transactions, arrival rate
2. Tellers—number of tellers, transaction processing rate
3. Waiting Lines—average length, average time per customer

The single activity of the system is processing of a transaction by a customer. This activity depends upon attributes of the customers and tellers and affects the attributes of the customer waiting line.

In order to develop the model further, several pieces of data are necessary. Methods for obtaining and verifying data are discussed in later chapters.

The process of constructing a simulation model is quite similar to the development of computer programs and digital hardware. In all cases, a systematic approach is used to implement an algorithm. Therefore, many of the principles of structured programming and hardware design are applicable to simulation modeling. The commonality among these three tasks is that all require a high-level system description and a well-defined procedure for the implementation of the model.

Principles of System Modeling

1. Modularity—divide system into logical subsystems each of which is conceptually simple
2. System diagramming—use a high-level diagram (i.e., flowchart) to relate subsystems
3. Relevance—include only pertinent information in the model
4. Understandability—model should be as straightforward as possible; terminology should be standard
5. Verification—check the structural and computational accuracy of the model

The most common question asked in reference to modularity is "How big should a module be?" There is no standard numerical answer. A rule of thumb is

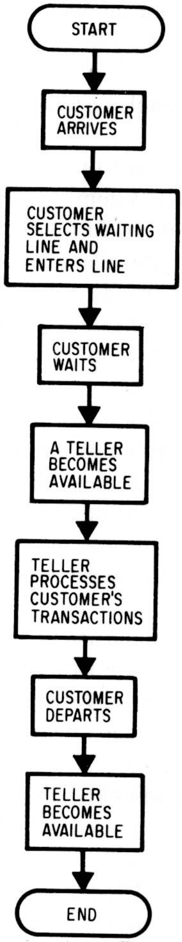

Figure 1.2 High-level Diagram for Teller Subsystem

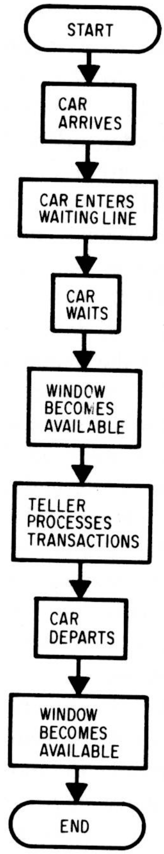

Figure 1.3 High-level Diagram for Drive-in Window Subsystem

that a module should describe one distinct portion of the system. Most such subsystems can be described with a one- or two-page diagram.

EXAMPLE 1.1

Let us consider the application of these modeling principles to a bank simulation. Since we have not discussed any implementation languages, our modeling will be carried out at a very high level. Initially, the modeling process must begin from a problem statement.

Problem Statement: Determine the optimum number of tellers and the optimum waiting line organization for a bank with up to five inside tellers and a drive-in window.

Let us construct a high-level model of the bank system using the five principles as guidelines.

1. *Modularity*. The system can be divided into two subsystems: the inside tellers and the drive-in windows. These subsystems are in fact completely independent. Each of the subsystems could be further subdivided if necessary to describe the arrival of a customer, the selection of a waiting line, and the processing of the transactions. Since we do not require a great amount of detail, two modules—inside tellers and drive-in windows—will be sufficient. As will be shown in Chapter 3, the level of detail is adequate for a GPSS model.

2. *System Diagramming*. Figures 1.2 and 1.3 are high-level diagrams of the inside teller and drive-in window modules, respectively.

3. *Relevance*. As discussed in Section 1.1, only those attributes critical to the purpose of the simulation should be included for each entity. Of the possible attributes listed in Table 1.1, only the teller transaction processing rate and the number of transactions per customer are crucial in the evaluation of the bank model.

4. *Understandability*. In an effort to be consistent with the terminology throughout the model, it may be desirable to replace the term "car" with "customer" in the subsystem diagram of Figure 1.3. Strictly speaking, it is the customers and not the cars that engage in banking transactions.

5. *Verification*. A model should be thoroughly checked at each phase of its development. Statistical verification methods that can be applied once the model has been implemented are discussed in Chapter 6. In the early stages of the development of the model, the structure can be checked to ensure that the model describes the behavior of the real system. A step-by-step manual simulation using the subsystem diagrams is a very useful verification technique.

1.3 SYSTEM SIMULATION

System simulation is the technique of using a dynamic model to describe the behavior of a system with respect to time. It is important to note that the above definition does not explicitly state that computer programming is required in a simulation. However, a system simulation does involve the study of dynamic, not static, models. For example, a program that solves a set of equations indicating the energy requirements of a large building for a given set of environmental parameters is not considered a simulation. However, if the program were expanded to allow for the projection of energy requirements for an arbitrary time span with varying environmental requirements, it would become a simulation of the energy system of the building.

1.4 SIMULATION STUDIES

A *simulation study* is an attempt to answer a well-defined set of questions by means of system simulation. In the case of the bank teller model used in this chapter, the goal of the simulation study is to determine an optimum number of open teller stations.

The definition of simulation study should be interpreted very liberally. The "well-defined set of questions" does not restrict the person carrying out the study to a rigid, preset group of topics to be explored. A simulation study must have a purpose even if it is somewhat vague, such as "determine the internal structure of the system." Many simulation studies can be quite flexible, evolving as the study progresses. This is characteristic of research environments. In most production or planning situations the concept of an invariant statement of simulation purpose is carefully followed.

The other portion of the simulation study definition that requires careful interpretation is the phrase "attempt to answer." A simulation model mimics a real-life system. It is not identical to the system. Results from simulations are projections of the expected behavior of the system being modeled. The accuracy of this projection is heavily dependent upon the nature of the simulation. Karplus [1.1] has characterized the reliability of simulation results by the "hardness" or "softness" of the underlying discipline. Simulation studies in the electrical and physical sciences can produce accurate numerical results. However, in the humanities and social sciences, simulations are intended to identify trends and critical areas rather than to quantify social or behavioral phenomena. See Chapter 9 for an expanded discussion of the value of simulation in various disciplines. For example, a general rule of thumb proposed by Paul Roth for simulation studies of computer systems is that numerical results obtained from such studies be considered accurate within 20% [1.2].

Simulation studies are performed for a wide variety of motives. For purposes of discussion, the reasons for simulation studies can be grouped into the following four categories:

1. *Performance Evaluation.* Project the behavior of an existing or proposed system under a wide range of environmental conditions. In cases where it is impractical or too expensive to observe system behavior in a real environment, simulation is a useful alternative. Instances of simulation studies in this category are battlefield simulations, aerodynamic studies, and computer network modeling. If a large company determined that it required additional computing resources, two alternative solutions are adding a large computer to a central loca-

tion or adding several small computers in remote locations. A simulation study can be used to project the performance effects of each alternative.

2. *Design Aid*. A simulation model of a system under development is often used in making design decisions and determining the probable effects of alternate design schemes. Simulation can be a very cost-effective mechanism for choosing directions and determining the critical points in the development of a system. Automated design systems are common in the electronics industry. These systems permit engineers to specify the components and connections of a circuit and then simulate the circuit to indicate its behavior under all possible conditions. Based upon the simulation results, the engineer modifies or accepts the design.

3. *Structural Investigation*. In many scientific fields, a study concentrates upon a system whose external behavior is observable but whose internal structure is unknown. Under these circumstances, the investigator develops a hypothetical system model and exercises the model by simulation in a number of environments. The validity of the model is determined by comparisons with observed system behavior. Simulations of this type are frequently carried out by biological and life scientists in the investigation of cellular microorganisms. Simulations have proved an invaluable aid in determining the structure of many submicroscopic organisms. Laboratory tests measure the organism's behavior in carefully selected environments. The researcher applies his/her knowledge of similar systems to create a simulation model of the organism in these environments. The simulation models indicate which hypothesized structures for the organism correctly describe its behavior in those environments.

4. *Project Planning*. A large number of system models are developed for the sake of projecting the future behavior of the system. Many socioeconomic systems are simulated in order to estimate the long-term effects of policy decisions. This area of simulation requires the utmost care in the interpretation of the projections obtained as output. An example of this type of simulation study is a project in the state of Oregon that modeled the economic and environmental effects of administrative policy decisions [1.3].

1.5 CONDUCTING A SIMULATION STUDY

Although the emphasis in many simulation courses is on the programming aspect of simulation, programming the model is but one step in a complete simulation study. The stages of a simulation study that are listed here occur in simulations conducted in both classroom projects and practical applications. The main difference in the two situations is that in a classroom project the emphasis is on model development, whereas in the practical environment the emphasis is on model application. Once a model is developed and successfully executed in a class assignment, it is generally abandoned. In industrial applications or

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