INTRODUCTION TO

COMPUTER SIMULATION

A SYSTEM DYNAMICS MODELING APPROACH

NANCY ROBERTS
DAVID ANDERSEN • RALPH DEAL
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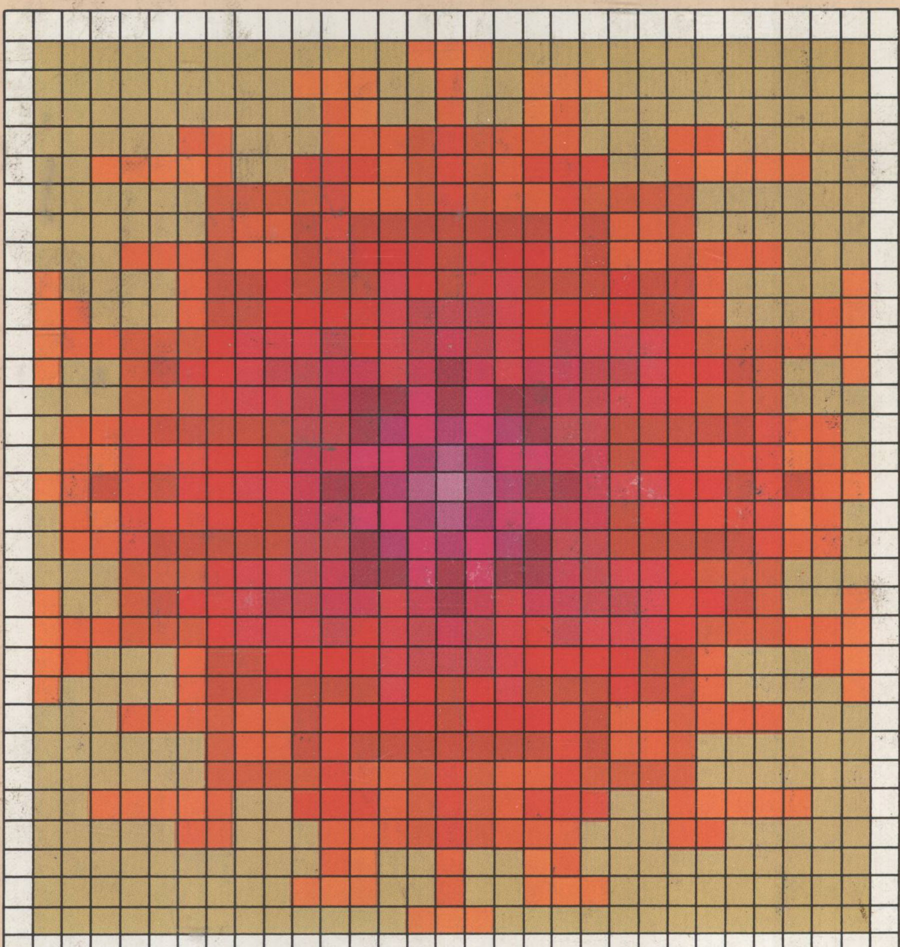

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INTRODUCTION TO COMPUTER SIMULATION: THE SYSTEM DYNAMICS APPROACH

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To our teachers and friends,
JAY W. FORRESTER
EDWARD B. ROBERTS

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FOREWORD

We live in a changing world. People grow, business conditions fluctuate, personal relationships develop, major industries come and go, population increases, water shortages worsen, and scientific discoveries increase. Our principal concerns arise from change—growth, decay, and fluctuation.

Change is a central concern in every human activity. The doctor tries to improve a patient's health; a parent tries to enhance a child's character and ability; a student tries to increase his or her competence; an engineer tries to raise the efficiency of a manufacturing process. Everywhere, people are taking actions to accomplish change.

But the processes of change have not been presented in an orderly way in our educational institutions. The dynamics of change have seldom been taught as a basic foundation that underlies all fields. The processes of change have not been organized so that they can be taught at all educational levels, even though a child, from his or her earliest awareness, begins to cope with change and to build an intuitive awareness of change. There are several persuasive reasons for teaching the processes of change as a formal academic subject.

First, the dynamics of changing conditions can become a universal foundation underlying all fields of endeavor. With a solid understanding of the structures that cause change, a person acquires a degree of mobility between fields. If the behavior of a particular structure is understood in one field, it can be understood in all fields. The same structures, each with its own characteristic behavior, are found in medicine, engineering, economics, psychiatry, sociology, management, and the everyday experiences of living.

Second, although life equips us with an intuitive feel for the dynamics of change, our intuition is reliable only in very straightforward situations. In the more complex dynamic structures, which increasingly dominate our lives, the intuition carried over from simple systems is misleading. As an example, in simple systems we learn that cause and effect are closely related in both time and space; in touching a hot stove, the hand is burned now and it is burned here. We repeatedly learn to expect a close association between action and the result. In more complex systems, however, the cause of a symptom may lie far back in time and in a remote part of the system. Only through study of structure and behavior can we develop intuition that is reliable when confronted by complexity.

Third, studying the dynamics of change is fun. It is challenging. It is meaningful because it couples with each person's life and problems. To understand the processes of change is to understand the surrounding world. If we understand our world, we can hope to improve it.

This book is a door leading to understanding of change. It should provide a glimpse of how things are interrelated, how humans and nature evolve, and how we can influence our future if we understand how that future is being shaped. With this book may come a deeper awareness of political processes, an improved grasp of rising and falling economic activity, and a clearer perception of physical and social behavior. A better understanding of change in turn raises the hope for an improved society, a more favorable relationship between humans and nature, and prospects for greater international understanding.

JAY W. FORRESTER

PREFACE

Development of an introductory curriculum in computer simulation has been a project spanning almost ten years and passing through three different stages. The initial work, essentially a dissertation project of Nancy Roberts, was the development of materials to teach the basic concepts of system dynamics.

The second stage was initiated when several people joined together in an informal group to consider the possibilities of teaching both system dynamics concepts and computer simulation to a broader audience. The broader audience had two important dimensions: people who were younger than the graduate students currently being introduced to system dynamics, and people not necessarily having a strong mathematics background. High school students and college undergraduates were chosen as appropriate target groups. In its final year, this second stage had funding to write and pilot-test these materials from the U.S. Department of Education, Program for Environmental Education (Grant #G007903439).

During the last stage of the project the materials were carefully revised, based on additional use at several educational levels and reviews from many readers. The authors' major revisions have therefore attempted to make this text appropriate for anyone, from a variety of backgrounds, wanting an introduction to system dynamics concepts and computer simulation.

Pilot testing of the materials has demonstrated that a mathematics background of algebra is all that is necessary for developing models in the DYNAMO computer language. No prior computer experience is needed.

An Instructor's Manual for this text is available which includes: suggestions for different ways to structure a course based on this material; an explanation of how to write system dynamics models in the BASIC language if DYNAMO is not available, as well as the BASIC program needed for the modeling; and suggestions for more advanced research topics outside the scope of this introductory text. The answers to the exercises not included in Appendix B are also available on request.

ACKNOWLEDGMENTS

The pilot-testing of these materials during the grant year was made possible by the generous donation of DYNAMO simulation software to the cooperating institutions by Pugh-Roberts Associates, Inc., Cambridge, Massachusetts. We are especially appreciative of the assistance of Jack Pugh in helping us with many of the installations.

In addition to this financial support, the project had the intellectual and moral support of many people during the years of conceptualization and development. In particular, three system dynamics faculty members have supported and encouraged the authors over a long period of time.

Edward Roberts, professor at the Massachusetts Institute of Technology (MIT), has been teaching, tutoring, and giving confidence to the first author for twenty-six years. It was through his advice that the original elementary level materials were developed. His continuing advice, guidance in conceptualization, and meticulous editing have enabled this book to be completed coherently. Ed wrote Chapter 22, as well as several smaller sections throughout the text to fill voids he perceived. In addition, Ed served as dissertation advisor for three of the other four authors during their doctoral years at MIT.

Professor Jay W. Forrester, as founder and head of the MIT System Dynamics Group, has often stated that some of the most insightful questions and comments about system dynamics works have come from high school and undergraduate students. Jay has long been supportive of the possibility of writing an introductory curriculum. He worked with the group for three years while Nancy Roberts was a Research Associate with the MIT System Dynamics Group. During this formative stage of the project, Jay guided the group in its initial notions of how system dynamics might be introduced to people of various backgrounds and ages.

Donella Meadows, professor at Dartmouth College, former member of the MIT System Dynamics Group and a founder of the Dartmouth System Dynamics Group, has long been concerned with pedagogy. Some of the computer models used in the last two parts of this book are variations of models developed by Dana over the years for her own classes.

Several additional people have been involved in this undertaking at various times during the past years. George Richardson, who taught system dynamics for many years at Simon's Rock Early College, worked with the group in conceptualizing the project, helped in writing the grant proposal, and developed several of the examples throughout the text. In addition, George wrote much of Chapter 24, as well as the SYSDYN software package (included in the Instructor's Manual) that permits writing system dynamics models in BASIC if DYNAMO is not available.

Joining the staff for the grant year were George Hein, professor at Lesley College, and Nancy Dyer, Lesley College graduate student. They were responsible for developing the grant evaluation instruments, and collecting and analyzing the evaluation data.

Also joining the staff during 1980–1981, the funded year, were Tanette Nguyen McCarthy and Marian Steinberg, graduate students at the State University of New York at Albany. Tanette and Marian helped David Andersen as co-authors of Part Three, contributed many ideas at meetings, and did writing for some of the other parts of the text as well.

Helping in formulating and writing the Urban Growth modeling project, Chapter 20, was Khalid Saeed, currently on the faculty of the Asian Institute of Technology.

The dedication of the secretarial staff enabled the curriculum to be developed and the book written. Headed by Barbara Woodring who, on numerous occasions, took initiative that turned chaos into a semblance of order, the staff successfully met a variety of deadlines. Aiding Barbara in times of overload were Mary O'Reilly and Ann Davis, Lesley College department secretaries who most competently and willingly gave helping hands.

The authors convey a deep sense of appreciation to the several faculty members who criticized, edited, discussed, and finally pilot-tested these materials with their students during the spring of 1980. Some of the most meaningful and practical comments came from these cooperating teachers and their students. One of these teachers, Jonathan Choate from Groton School, Groton, Massachusetts, accepted the responsibility for organizing and writing the initial draft of the Instructor's Manual. Particularly helpful were the suggestions of Michael Goodman who used the materials in a graduate course he taught at Lesley College during the summer of 1981.

Finally, the authors thank two people who greatly added to the final readability and appearance of this material. Diane Senge's exceptional quality graphics work has generated all the text figures. The delightful sense of humor embodied in Carole Roberts' illustrations will keep the students' feet on the ground as the power of creating computer worlds goes to their heads.

In spite of some tense moments, the curriculum-development and book-writing project has been a truly rewarding experience for the authors. We hope these materials will be of benefit and pleasure to others.

August 1982

Nancy Roberts
David F. Andersen
Ralph M. Deal
Michael S. Garet
William A. Shaffer

CONTENTS

PART I

BASIC CONCEPTS OF SYSTEM SIMULATION

OBJECTIVES

Part I introduces the concepts key to this text, composed of:

1. Computer simulation, a method for understanding, representing, and solving complex interdependent problems;
2. The system perspective, including three critical aspects: cause-and-effect thinking with causal-loop diagrams, feedback relationships, and system boundary determination.

CHAPTER 1

SIMULATION, MODELS, AND SYSTEMS

SIMULATION AND MODELS

Originally, the word *simulate* meant to imitate or feign. This meaning suggests one important characteristic of simulation: to simulate is to imitate something. For example, children playing house are simulating family life; fighter pilots flying a training mission are simulating actual combat.

Simulation generally involves some kind of model or simplified representation. During the course of a simulation, the model mimics important elements of what is being simulated. A simulation model may be a physical model, a mental conception, a mathematical model, a computer model, or some combination of all of these. For children playing house, their "model" is the toys they are using, along with imaginary characters and settings. For an air force pilot in training, the model might be a mock-up fighter plane.

Many simulations involve physical models. For example, the United States Army Corps of Engineers has constructed a small-scale physical model of the Mississippi River, which is used to study ways of reducing the impact of flooding. The behavior of a major river is quite complex and cannot be studied through direct experimentation on the actual river. Therefore engineers have to rely on experiments using the model. Wind tunnels and wave tanks are other forms of simulation in which a physical model is used to imitate a larger system. For instance, a scaled-down model of a plane or ship can be constructed out of wood or other material, and then placed in a wind tunnel or wave tank. Using a wind tunnel, air is blown past a scale model of a plane to examine the plane's aerodynamic properties. Similarly, by using a wave tank a ship model can be subjected to waves to see how it performs.

Since physical models are often relatively expensive to build and unwieldly to move, mathematical models are often preferred. In a mathematical model, mathematical symbols or equations are used (instead of physical objects) to represent the relationships in the system. To perform a simulation us-