MATHEMATICS IN SCIENCE AND ENGINEERING

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Systems and Simulation

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Foreword

That the history of science and mathematics is intimately entwined with the history of mankind has been emphasized by many historians of science; Sarton, in particular. Great political and cultural surges have always reflected themselves in corresponding bursts of scientific and mathematical creativity. This has been the case from the time of Archimedes through the times of Newton and Leibniz to the present. One aspect of the current intellectual explosion has been that fields far removed from the conventional domains of mathematics and its applications are now being studied and cultivated with great zeal. Among these fields, we may mention economics, management, organization theory, psychology, and biology and medicine.

Actually the beginning efforts in these areas stretch back into time. At the end of the eighteenth and the beginning of the nineteenth century, for example, there was a great deal of interest in what is now called "operations research" and mathematical economics. But a lack of computers and a lack of urgency combined to prevent any extensive development. World War II created the urgency, and the hasty work done during that period under great pressure of time gave some idea of what could be accomplished in these areas using sophisticated concepts and modern mathematical techniques. In the years following the war, there has been an opportunity to examine the problems and solutions with the care and effort required to produce a new discipline called systems analysis.

The book by Chorafas is a building block in the firm foundation of this new discipline. Ideas, concepts, and methods have been borrowed from the traditional domains, and new types of problems have been treated in this fashion. From this amalgam has emerged new ideas, concepts, and techniques which have been applied to treat the more complex questions and which have then been applied to problems within the classical domain. This is the usual feedback that occurs when a new field is explored. It is a fair exchange for both sides.

Many of the most important problems confronting our society are related to the analysis, behavior, design, and control of systems. The reader forced to face the complexities of reality will find this volume of great value; the mathematician looking for new fields to conquer and new categories of problems to tame will equally find it of interest and value. It is with pleasure that I welcome this book into our series.

RICHARD BELLMAN
Santa Monica, California

Preface

Professor Chorafas has again rendered an invaluable service to many of us in describing some very real problems which arise in our modern world, and the means now at hand for rapid, accurate and comprehensive solution. For the technical planner, and the engineer, this book must surely become a ready reference work of great worth. Business and industrial management will find that it outlines new methods of attack on their unsolved difficulties which are created by the complexities of living in a highly developed and competitive economy. Professor Chorafas feels that we have reached a point in almost every sphere of human activity and quasi-achievement where all major problems of business, industry, and government can be formulated and presented as systems of mathematical logic.

A system is defined broadly as a "group of interdependent elements acting together to accomplish a predetermined task." The objectives, interrelationships, and constraints of the system are recognized and isolated, and in turn stated through the true and universal language of mathematics. When we have the problems of the age reduced to the form of equations and quantitative data, we have the abstract and the real, which is the true concern of mathematical analysis and mathematical systems.

The new and promising discipline of *system analysis* seeks to determine the optimum means for accomplishing the task described in the problem statement. The *system analyst* is more than an engineer, a mathematician or an accountant. His education involves these subjects and many others, including psychology and the general theory of knowledge. System analysis presents a rewarding and exciting career opportunity for the bright members of the new generation; clear conceptual thinking, analytical ability, and the power of synthetizing many different factors into an organic whole are required to excel in this new discipline. Knowledge in many fields is necessary, but narrow specialization in any specific area must be avoided, in order to maintain an unbiased "generalist" approach to the entire problem.

Once the system has been defined in mathematical terms, its solution may be found by the technique of simulation, that is, by investigating the performance of the actual system through an analogous system, more accessible to the system analyst. Through the observations made on the simulated system, we can study the characteristics, test the reaction, and predict the performance of the original system.

Because of the complexity of the system studied, analog and digital computers are almost always necessary for simulation studies. A simulator is a device that puts a physical process or concept or a mechanical, electronic, biological or social system into such a representative form that the phenomenon can be imitated with a computer where there is correspondence between problem parameters and variables and those of the computer. Professor Chorafas's examples of successful simulations are widely drawn, thoroughly explained, and cover a significant number of civil and military applications.

Many complex industrial processes are ideally simulated on digital computers, particularly where the product is made up of many parts. For such a simulation, it is necessary to describe all parts required in the finished product, the machines used to produce each part, the time used for each operation, the relationships between operations, and the capacity of each machine. The computer program will determine the operations sequence, bottlenecks in the production flow, schedules of optimal nature, so that the production time and costs are reduced.

Management gaming lends itself to digital computer simulation. The human player in the game determines the various controllable aspects of his business such as budgets for advertising, for engineering, for research, volume of production, etc.

Programs are fed into the computer which then simulates the business operation and prints reports which may indicate sales volume, inventory, production capacity, and the state of profitability of the business in the future.

Professor Chorafas elucidates some of the most challenging problems of systems engineering and some of the pitfalls. They include, as we learn, the need for designing, predicting performance, building and operating vast and complicated elements in many combinations.

The definition of the word "system" presented above is disarmingly simple and very general. But systems engineering emphasizes the requisites that are necessary for optimum performance under varying conditions of load, environment, information inputs, and even, perhaps, the metabolism of the engineer. When total systems are brought into play, system design, realization, and analysis may require the engineer to be scientist, both natural and social, with the hint of the "specialist." The systems analyst or engineer must have a very broad outlook indeed.

The book itself encompasses broad fields. It takes us through Industrial Operations, Inventory Controls, Tools for Data Generation, Management Data in Mathematical Form, etc. It will make a good book for reading by the computer industry itself which is ever more concerned with solving the problems of business (including its own ?).

The computer is becoming an essential component of modern management information systems, and an indispensable aid in decision making for business fighting its way through the competitive flood, on an international scale. Parallel to the explosive development of the computer, the techniques used by modern business management must become more advanced and sophisticated, and must be based on the most recent developments of science and technology. The book of Professor Chorafas is a timely and worthy contribution toward this goal.

F. Gordon Smith
Vice President, UNIVAC Operations
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Introduction

As the achievements of science become more numerous, more inspiring, more divorced from the little corner of common sense familiar to all of us, it becomes increasingly more necessary as well as increasingly more difficult for an individual scientist to maintain a firm intellectual grip on the various ramifications of a chosen field of knowledge. In a certain way, the individual scientist either becomes dependent on his fellow scientists for an understanding of allied fields, or he finds himself obliged to get acquainted with at least the fundamentals of new theories and new applications. This is not always an easy task since along with the increasing complexities in the sciences themselves comes an increased volume of routine work and of record keeping.

The purpose of this book is to present, explain, and discuss in a fundamental manner, some of the mathematical systems which have become popular in professional practice in recent years. Since World War II we have experienced an increasing development in all the domains of man-made systems, from pure theory to technological and other applications. The wide range of these applications defines the subjects to be discussed in the present work, both practical and theoretical in nature; they have been selected because they constitute the keys to a great variety of fields in science, technology, and management.

This work starts with a discussion of certain fundamental notions—notions concerning mathematical abstraction and systems work, the nature of simulation studies, and the development and use of analytical models. It is only logical that this general-type discussion be followed by a group of chapters that dig deep into the mathematics of the simulator. The writing, developing, and testing of equations are given roles of first importance. This is also true for data generation, data reduction, and the use of certain methods for the solution of equations.

The applications part of the present book is divided into two major groupings. One deals with the simulation of managerial systems, and it involves eight chapters. The other treats applications characterized by their technological nature. This last subject involves six chapters, three of which concern the flow of distinct particles and the other three center on hydrological applications. To bring another facet of this great art under proper perspective, the work closes with two chapters on analog simulation.

This text has been prepared with due consideration to the fact that in the course of the last ten years, our ways of thinking about performance of integral, purpose-accomplishing systems have evolved virtually to the point of creating a new technical discipline. The ways of thinking are not new in the sense that they consider the contribution of all elements of a system toward the accomplishment of a specific purpose. Such considerations, in varying degrees of refinement, have always been a part of planned endeavors. Essentially, what is new is the ability of modern scientists, mathematicians, and engineers to penetrate into the unknown through systematic experimentation and an analysis of the crucial factors. This analytic thinking is part of the foundation of the amazing technological development we are experiencing.

Some argue that our new technology needs a "new kind" of people. What nonsense! Our technology needs people well educated in the latest theories, methods, and techniques; people possessing the marvelous mixture of a broad background and a good deal of creative imagination. For people with creative imagination, any sphere of human activity will do. To some extent, whether they become officers, priests, tradesmen, managers, engineers, or scientists depends on circumstances.

DIMITRIS N. CHORAFAS

December, 1964

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CHAPTER 1

Mathematical Abstraction and Systems Work

One of the strongest motives that lead men to art and science is escape from everyday life with its painful crudity and hopeless dreariness, escape from the fetters of one's own ever-shifting desires.

A finely tempered nature tends to slip from personal life into the world of objective perception and thought. This desire may be compared with the townsman's irresistible longing to leave his noisy, cramped surroundings for the silence of high mountains, where the eye ranges freely through the still, pure air and fondly traces out the restful contours apparently built for eternity.

Man tries to make for himself in the fashion that suits him best a simplified and intelligible picture of the world. He then tries to substitute this cosmos of his own for the world of experience, and thus to overcome it. This is what the painter, the poet, the speculative philosopher, the writer, the natural scientist, and the systems analyst[1] do, each in his own fashion.

Each one of these men is an artist in his own sphere of endeavor; and, the greater the artist the greater the art. The philosopher, the writer, the researcher all work on those subjects which stimulate them the most, which answer their mental worries, which generate for them the most thought and promote the human search into the mental unknown—the highest activity a human being can perform.

People of this kind make the cosmos they conceive and its construc-

[1] Webster defines "system" as "an assemblage of objects united by some form of regular interaction or interdependence." In the discussion to follow, our reference will be to medium or large scale physical, technological, or administrative ensembles, whose study requires the work of the specialist.

We will use the words "systems analyst," "systems engineer," and "systems specialist," to identify a scientific discipline; persons versatile in conceiving, analyzing, experimenting, evaluating, and designing man-machine–environment systems made for a predetermined objective and according to preestablished criteria. We will use the words "researcher" and "experimenter" more precisely for persons involved in these aspects concerning simulation work and experimentation.

tion the pivot of their emotional life, to find in this way the peace and security they cannot find in the narrow whirlpool of personal experience. But work in the field of mental abstraction demands the highest possible standard of rigorous precision in the description of relations. Here exactly is the point where the two different cosmos separate. That of the poet, the painter, and the writer will continue to be expressed in a qualitative manner; while the natural scientist and the systems analyst require for their expression a quantiative form that only mathematical language can provide.

Abstraction and Reality

In the broadest sense, mathematics may be separated into two classes. One class deals with the symbols, their combinations and properties, in a formal way. The other class concerns itself with the meaning of the symbols: the significance of the system related to the real world. Of the three theoretical sciences—philosophy, mathematics, physics—mathematics made the earliest advances with respect to accuracy and truth. The aim of theoretical science is neither action nor production, but the acquiring of a scientific truth.

Man with his receptors has no deep contact with physical reality. The interaction of his senses with nature gives him the impression he calls empirical knowledge. This empirical knowledge is only what his senses and their extensions can observe and describe. With the data he obtains, he is led to abstraction and idealization, and at that point mathematical analysis takes over. The aim is to formulate a comprehensive theory that will describe observable phenomena and lead to verifiable predictions.

Research workers are often required, by the nature of their profession, to spend years of anxious searching in the dark, with nothing else to warm them but their own fears, with continuous extensions in their search, with alterations of confidence and doubt. Behind the tireless efforts of the investigator there is a stronger, more mysterious drive. It is existence and reality that he wishes to comprehend.

In the course of the evolution of human knowledge we have experienced the growth of new and promising disciplines. One of them is systems analysis. Its foundations have been derived from studies of dynamic systems and their functioning components. A system is a group of interdependent elements acting together to accomplish a predetermined purpose. *Systems analysis* is an attempt to define the most feasible, suitable, and acceptable means for accomplishing a given purpose.

The systems analyst, like the natural scientist, must limit his range of endeavor. The natural scientist contents himself with describing the most simple events that can be brought within the domain of his experience. All events of a more complex order are beyond the power of the human intellect to reconstruct with the subtle accuracy and logical perfection which the theoretical physicist demands. For his part, the systems engineer must content himself with the study and analysis of complex technological systems, with the understanding of the nature and the workings of systems components, and with their synthesis into a working ensemble.

The study of systems behavior is not another whim. On the basis of his experience of the systems of today and by using his creative imagination, man needs to project into the future, to speculate on the systems of tomorrow. Projection into the unknown is based on unproven hypotheses. In our fast-developing technology we can never be sure of what the scientific truth of tomorrow will be. To say that we know tomorrow is to expose ourselves to bitter disappointments.

But what can be the attraction of getting to know the technological future only in a speculative manner? Does the product of such an effort deserve to be called a science or a great art? To answer such questions one should realize that even in the world of today we can never be sure that our conceptions represent the truth or that our formulations are unique and solidly determined. We are living in a world of shifting ideas. What we do know is sample data on a universe. Due to our human limitations we will probably never know the universe in its totality and the "truth" behind it, whatever that may be.

Systems study is very often confronted with problems of inference. On the basis of a sample we are required by the nature of our work to generalize as to the structure and the behavior of the whole; to speculate in the time domain with information from sample data obtained in a finite population.

In this tedious and uncertain work, the scientist is assisted by the fact the general laws on which the structure of natural and man-made systems are based claim to be valid for any phenomenon. With them it ought to be possible to arrive at the description or, in other words, the theory of every natural process including life. Man has often attempted to arrive at such a description. Conceivably, he might have arrived by means of pure deduction if that process of deduction were not far beyond the capacity of the human intellect. This is the approach taken by philosophers and some of the artists.

The state of mind which enables a man to perform work of this kind is akin to that of the religious worshipper or lover. The daily effort