PROSPECTS FOR SIMULATION AND SIMULATORS OF DYNAMIC SYSTEMS

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Preface

It can be claimed with some validity that the story of man's progress in science and technology is actually the story of his success in the use of analogy and his progress in simulation. Through analogy with familiar and simple events he has sought to understand the more complex phenomena of the world in which he lives. To test his analogical conclusions he has had to set up experiments and build equipment and laboratories which simulate the natural conditions he wishes to understand.

Since, by its very definition, an analogy or simulation cannot be identical with the realities of nature it attempts to represent, the danger that a crucial factor has been ignored or subordinated is inherent in the formulation of all analogous problems and simulations. This defect is especially likely to occur in analytical simulations, where mathematical abstractions and methodology are substituted for the models and other simulation devices of the conventional experimentalist. The devices resemble, at least in form, the natural phenomena under investigation, whereas the mathematical abstractions and methodology depend upon axioms not necessarily derived from observed natural phenomena.

As the horizons of man's understanding, inquiry, and technology expand, however, the demands for laboratory simulation expand proportionately. Experiments in which the parameters governing the behavior of the system under study can be varied at the will of the investigator become so complex that the creation of laboratory equipment to perform them strains the state of the art while its development and operation strains the state of the exchequer. As a result, modern research and technology have found analytical simulation not only expedient but also indispensable. It may be completely analytical, as in computational experiments, or it may be partially analytical through incorporation of the computational tool (analog, digital, or hybrid) in the laboratory setup as a crucial element for control, data processing, and other functions.

One of the drawbacks to the more general acceptance of the computer as a primary simulation tool by the scientific and engineering communities might be called an impedance mismatch between computer and human. Many people have intuitively believed this mismatch to be intrinsic to the computer-human relationship. To them the only advantage of the machine seemed to be its ability to compute much faster, with more accuracy and less fatigue than the human. However, the power of the modern computer is twofold. On the one hand, it processes masses of experimental data rapidly as well as providing control and precise registration of multitudinous sequential operations. Thereby it makes experiments practical that are impossible without it. On the other hand, when the computer is applied with proper analytical perspective and strategy, it can provide universal and relatively inexpensive simulation in its own right.

The relation of computer and human, moreover, is undergoing a radical change in which the interaction between man and machine is becoming ever more simple and rapid. The speed and capacity of computers have increased over the last two decades so that today computations can be made almost 10^8 times as fast as a man can perform them. Of more importance to the use of computers as simulation devices, however, are those developments which have made the machines easier to use. Formerly, output was usually an indigestible tabulation of a large volume of numbers. Today output can be graphic, thus summarizing instantaneously the computer results. Readout has been made simpler for the scientist or engineer who is not a computer specialist. For example, today instructions to a machine can often be given by merely typing simple near-English or by supplying graphic inputs which the machine reads and understands.

Thus, improvements in computers and, in particular, improvements in the ease of using them portend a new era in their use as simulators. It is therefore of interest to identify and explore those factors and trends which could either inhibit or accelerate this development. The most suitable vehicle for such an undertaking is the open forum, where scientific and engineering specialists can meet and focus their undivided attention on this subject in an environment of free, full, and frank discussion of the issues involved.

The Air Force Office of Scientific Research and the Westinghouse Defense and Space Center therefore sponsored a Symposium on the Prospects for Simulation and Simulators of Dynamic Systems to correlate the experiences of both the scientist and engineer in the use and design of simulation equipment and thereby provide perspective and source material on the fundamentals of simulation. At this Symposium, held in Baltimore, September 26 and 27, 1966, the eighteen papers which form the chapters of this book were presented—too many for detailed summary here; however, a few words on their interrelationships may be useful.

Topics discussed are categorized as relating to the use of simulation (user-oriented) or to the development, software as well as hardware, of simulators (supplier-oriented). In the first category are included atmospheric circulation, aeroelasticity, statistical mechanics, biophysics, biological mechanisms, combinatorial, nonquantitative, control, man-machine, and interdisciplinary problems, the emphasis being on problems which can be solved only by simulation. Organization structures of interest cover content addressable memories, nonnumerical machines, hybrids, on-line real-time multiaccess systems, and other man-machine combinations and systems which include the recognition of unusual events or data trends, the emphasis here being on those concepts of simulators and organizations which would be useful in the solution of such problems.

In the Symposium, sessions alternated between user-oriented and supplier-oriented papers, in order to restore the feedback between science and technology since the technological state of the art determines the sophistication of the simulations attempted by the scientist while the scientists' needs lead to advances in the state of the art.

In this volume all the user-oriented papers are presented together in the first half, while all the supplier-oriented papers are presented in the second half. As is often the case with a topic wherein method and purpose overlap, it is not possible to categorize every paper absolutely as either user or supplier, and inclusion in one part or the other of this volume is therefore a matter of emphasis, the decisions being made on the basis of the primary interests of the author.

In preparing the manuscripts for publication editing was kept to a minimum, thus permitting each contributor's personality and enthusiasm for his subject to be conveyed to the reader. Succinctness and uniformity in notation from paper to paper was sacrificed at times for clarity; what was thereby lost in professional polish in the volume is more than compensated for in ease of comprehension.

We are indebted to many individuals and organizations who helped make the meeting a success. In particular, the advice and aid of the technical session chairmen, C. V. L. Smith, M. Knapp, H. D. Block, and N. R. Scott, in organizing and conducting the technical sessions is especially appreciated. At the Westinghouse Defense and Space Center special mention is due Mr. Stanley Burik along with Mrs. Kathleen Skinner and Mrs. Virginia Rodriguez for their assistance before, during, and after the Symposium.

It is the hope of the editors that these proceedings will prove useful to others not only in gaining a fuller appreciation of the new horizons in research and engineering revealed by modern developments in simulation but also in helping them identify factors which require further research for understanding and application if those horizons ever are to be reached. We also hope that the reader will find study of these proceedings as stimulating an experience as the Symposium was to those who participated in it.

M. Rodgers

G. Shapiro

Baltimore, Maryland

January 1967

Opening Remarks

Dr. William J. Price

Executive Director
U. S. Air Force Office of Scientific Research
Arlington, Virginia

It is a pleasure for me to be here for this opening session of the symposium on simulation, and to greet you along with Mr. Trevor Clark and our other hosts from Westinghouse. We are very grateful for the fine accomodations which contribute so much to the success of a meeting like this. I wish to congratulate both George Shapiro of Westinghouse for his excellent job in arranging the symposium, and Milton Rogers, Chief of the Mechanics Division of AFOSR, who is the papers chairman. You both deserve all our thanks.

This symposium, I believe, is unique in its approach to simulation techniques in that it is broadly interdisciplinary, and carefully thought out to provide an interchange between researchers and engineers. You of the research community have problems which can only be solved by simulation. You engineers are selected specialists in conceiving simulations and novel organizations which may be used in the solution of such problems.

We are dealing here with the types of problems which both the researcher and the engineer find impossible or extremely difficult to solve with today's technology in instruments and computer systems as known to the researcher. Conversely, the engineers and industrial scientists find it difficult to communicate current and projected trends and thoughts in technology and system organizations. The symposium has been planned to bridge some of these differences in chosen areas. I know the interchange will benefit all of us here, as well as a broad range of the scientific and engineering community when the proceedings are published.

No doubt you have heard the comment that computer hardware development is far ahead of skills in computer use. It is not enough to use computer capability for question-and-answer dialogues that are determined a priori. To realize the full capability of computing machines we must, to an increasing extent, blend the machine into man's thinking processes. This is what simulations are trying to accomplish so that the machine is no longer merely an extension of man's computational capability, but is an instrument capable of predicting the interactions of exceedingly complex man-machine systems.

It is extremely appropriate that AFOSR help sponsor this symposium. With its nearly $40 million for basic research support each year, AFOSR has responsibilities for pioneering those areas of science that hold particular potential for Air Force technology. This symposium will advance simulation as a research technique, and will also significantly affect the rate of progress in many other fields. I think of AFOSR as providing communication first of all between the scientific community and the Air Force, and also, through our extensive program of support of conferences and symposia, as providing communication between the suppliers and users of research and research methods.

This group today comprises an excellent example of what has come to be called "invisible colleges," groups of scientists working on the frontiers of a given specialized area of interest. They are not grouped geographically, but rather are widely scattered—but their effectiveness is in their communication with each other. There is direct correlation between how rapidly research progresses and how well these members of "invisible colleges" communicate.

Thank you for the opportunity to participate in these sessions, and on behalf of AFOSR I wish to extend to you a cordial welcome and wish you a most profitable meeting.

Opening Remarks

Trevor Clark

Manager, Program Operations
Westinghouse Electric Corp., Aerospace Division
Baltimore, Maryland

It is a great pleasure to welcome this Symposium on Prospects for Simulation and Simulators of Dynamic Systems to the Aerospace Division of Westinghouse. Even prior to the formation of this division, Westinghouse designed and built the ANACON, a simulation facility which enabled us to develop the equipment for fire control, weapons control and other avionics tasks which have become the products of our division. In 1952 we opened our Analog Simulation Laboratory here. Since then it has grown to be one of the largest privately owned installations in the world.

The computer itself is supplemented by our own cockpit simulator; 3-axis gimballed platform; altitude simulator; a host of readout devices, ranging from the simplest cathode ray tubes to the most complex recording tables; and other accessories by the score. It has been necessary to design and build much of this equipment ourselves. As a result we have licensed our 3-axis table and our altitude simulator, and many of you may have copies of these products in your own laboratories.

About three years ago we began planning with the Naval Research Laboratories and in the near future our analog simulator will be interfaced with a digital facility which will give us one of the finest hybrid installations existing anywhere.

A typical simulation program in our facility is usually worked out in stages. We begin by simulating the entire weapon system on the simulator, then we mechanize various portions and substitute these as subsystems into the simulation until finally the avionics system has been completely mechanized.

In this way, for instance, the pilot is able to fly the avionics system on the simulator obtaining the optimum interface between man and machine prior to the time any mechanization takes place. These simulator flights continue as the various subsystems are mechanized. A large number of flights are simulated in the laboratory prior to the time any aircraft is involved.

The system is then installed in the aircraft or missile and is flown on the ground with the simulation facility still representing the aerodynamic, hydrodynamic or orbital motions of the vehicle itself. For this phase we move a portion of the simulator to the hangar along with the hardware which is installed in the aircraft. The pilot flies the plane without ever leaving the ground until we are satisfied that the mechanization meets the performance criteria. Only then do actual flights begin.

We have found this process to be extremely effective in the development of very complex systems. The facility has been extended to a great variety of vehicles in aerospace and in hydrospace as well. For instance, we have simulated the control system for underseas craft of various sorts and through this means have developed control systems peculiarly adaptable to various types of underseas missions. It is interesting to note that the generated response times and forces are many orders of magnitude different in the case of aerospace and hydrospace vehicles. However, the same simulator facility is able to accommodate a great diversity of shapes and surfaces in the two media.

During your visit we hope that you will have an opportunity to see a portion of these facilities and also to hear of some of the unique problems to which they have been applied. It is appropriate that this symposium on simulation should be held at our facility. We welcome you and know that you will find your attendance to be interesting and rewarding.

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On General Formulations of Simulation and Model Construction

by

S. M. Ulam

An attempt is made to formulate various mathematical definitions for the concept of "simulating" a structure or "pattern." Such patterns may be static, that is, not involving a change in time but, since we need not restrict ourselves to a fixed number of dimensions, we may think of the time variable as one of the dimensions and kinematic situations involving motions may be also treated similarly. This is true even of the possibility of simulating; i.e., simplifying, certain features of dynamic problems or of games.

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On General Formulations of Simulation and Model Construction

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Introduction

The idea of similarity in mathematics is very old. In fact, mathematics itself may be considered as a way of abstracting certain features of objects and treating them *per se.* Certainly in geometry, from its very beginnings, the idea of similarity of figures was introduced and studied very early, e.g., two figures or two solids are considered similar if they can be mapped into each other in such a way as to preserve, e.g., only the angles, not necessarily the distances. In general, given a mathematical structure, algebraic or geometric, one studies mappings of these structures on others, mappings preserving only certain, but not necessarily all, of the relations with which a given theory deals. These mappings need not even be one-to-one. Thus, in group theory, one deals with isomorphisms or homomorphisms. In topology, with homeomorphisms, i.e., one-to-one continuous transformations of a space into another space or, more generally, many-to-one continuous mappings. The idea of a "model" in mathematical logic and in foundations of mathematics has a somewhat different character: Given a system of axioms, we understand by a model of a system or of a theory a more "concrete" object. A model is found if one defines a concrete set of objects and relations between them—the relations satisfying the given axioms—and the model possesses perhaps some other, additional properties. It has therefore, at least potentially, more information: It may have other properties which are independent of the given system of axioms and rules. In this sense it is in a way larger than the original object.

The idea of a model in physical theories is, speaking logically, still of a different character. A physical theory is supposed to serve as a model or image of reality or of a segment of reality. In its mathematical formulation the theory deals only with certain selected properties of the physical world which are measured or computed from measurements. One does not really require a strict, completely precise agreement between the quantities as computed or deducted from the theory and the observed ones but one is satisfied if the agreement is good enough; i.e., one allows certain margins for error. This error may be considered as due to the imprecision of measurements or to the admittedly simplifying assumptions made in the theory.

ε-Morphism

In mathematics itself one may take a similar point of view: instead of speaking of transformations or correspondences between two mathematical structures which preserve exactly a given set of relations, one can study transformations which do not change these relations by more than a specified amount, a given $\epsilon > 0$. In the few pages that follow, we shall try to give examples of these "ϵ-morphisms." A simple example can be furnished by the following: We shall call a function $f(x)$ linear if $f(x + y) = f(x) + f(y)$ for all values of x and y. This strict equality can be replaced by a less stringent requirement: We may require that the left-hand side and the right-hand side are only approximately equal, that is to say, we have for all x and y

$$|f(x + y) - \{f(x) + f(y)\}| < \epsilon$$

Here $\epsilon > 0$ is a number given in advance. In other words, we may require that the equation defining linearity holds only approximately. In this case one can prove (this is the result of D. H. Hyers) that a function satisfying our inequality is not very different from some function which satisfies the strict linearity property. In other words, any solution $f(x)$ of our inequality must of necessity be near to a solution of the strict equality. Thus, given such $f(x)$ there exists a $g(x)$ where $g(x)$ is a linear function and, ***for all*** x

$$|f(x) - g(x)| < \epsilon$$

This result holds true even when x is not necessarily a real number but a vector in n-dimensional space. More generally, the equation expressing the isomorphisms of two groups is sometimes "stable" with respect to such a change (for certain groups G). Two groups, G and H, are called isomorphic if there exists a mapping of the group G into the group H such that $f(x \cdot y) = f(x) \cdot f(y)$. The first ($\cdot$) sign means multiplication of elements in the group G; on the right-hand the ($\cdot$) means multiplication as defined in the group H. In a case when G and H, in addition to being purely algebraic structures like groups, are endowed with the notion of distance between their elements, one could require a less stringent relation and speak of an approximate or an ϵ-isomorphism by postulating that for all x, y, we should have merely

$$\rho\{f(x \cdot y),\ f(x) \cdot f(y)\} < \epsilon$$

Here ρ denotes the distance between the elements. For certain groups all ϵ-isomorphisms must of necessity be close to a strict isomorphism. A few more examples: A transformation of a metric space, say of the Euclidean space on itself, which preserves all the distances, is called an isometry. One can study transformations of such a space into itself which, while not preserving strictly all distances, have the property that the distances do not change much; i.e., the distance between any two points differs from the distance between their images by at most ϵ, a positive number given in advance. In this case again it is possible to show that such an ϵ-isometry is, of necessity, near to a strict isometry. One could formulate analogous problems about ϵ-similarity, i.e., require that mappings do not change any angle by more than a given amount. One can consider an ϵ-similarity between two algebraic structures provided they are endowed with a notion of distance between the elements. More generally yet, one could investigate the stability of various mathematical definitions by posing the following problem which, formulated here only vaguely, is: If we change slightly, i.e., by less than $\epsilon > 0$ the hypotheses of a statement, will the conclusion be still valid within ϵ or say $k\epsilon$—with a fixed value of k? In order to obtain a precise formulation of such a general question, one has to define a notion of distance between statements; a notion which, speaking intuitively, would have to satisfy the desideratum: statements differing in distance by less than ϵ should have approximately the same meaning.* Some mathematical theories deal with qualitative properties of mathematical objects. Topology considers two geometrical figures, or sets of points, as identical if one of them can be mapped into the other in a one-to-one continuous fashion (without "tearing" or "gluing together") without regard to changes in distances between points. Poincaré defined this branch of geometry as a science of those properties of figures which remain the same even if sketched by unskillful draftsmen. One might relax these requirements and allow mappings which, while still continuous, identify different points by transforming them into the same point but postulating that points which are far apart (with distance between them greater than a given $\epsilon > 0$), shall have distinct images. These ϵ-homeomorphisms still preserve certain global properties of objects.

*For a discussion of some properties of the notion of stability in mathematics, see pp. 63 to 69 of "A Collection of Mathematical Problems," Interscience Publishers, New York (1960).