

THE SYSTEMS APPROACH

*Fresh Solutions to Complex Problems
Through Combining
Science and Practical Common Sense*

Simon Ramo, Ph.D.

and

Robin K. St.Clair, Ph.D.

Index

Title

About the Authors

| | | |
|--------------------|---|-----|
| Chapter I | The Technology World | 1 |
| Chapter II | Systems-Something Old, Something New | 16 |
| Chapter III | In Contrast, the "Piecemeal" Approach | 23 |
| Chapter IV | The Systems Approach or Chaos | 34 |
| Chapter V | System Design, a Necessary Step to Component Availability | 46 |
| Chapter VI | The Tools and Talents of the Systems Team | 57 |
| Chapter VII | Cost Effectiveness and Tradeoffs | 73 |
| Chapter VIII | Optimization, Mathematical Modeling, and the Computer | 82 |
| Chapter IX | Function and Flow of Information, People, and Materiel | 95 |
| Chapter X | Feedback, Instability, and Nonlinearity | 101 |
| Chapter XI | The Impact of New Technological Components | 113 |
| Chapter XII | Applying Common Sense and Science to Civil Problems | 120 |
| Chapter XIII | The Future of the Systems Approach | 138 |

THE SYSTEMS APPROACH

THE SYSTEMS APPROACH

*Fresh Solutions to Complex Problems
Through Combining
Science and Practical Common Sense*

by

SIMON RAMO, Ph.D.,
Co-Founder of TRW

and

ROBIN K. ST. CLAIR, Ph.D.,
Systems Integrator for TRW

**KNI, INCORPORATED
ANAHEIM, CALIFORNIA**

THE SYSTEMS APPROACH

COPYRIGHT © 1998 BY TRW, INC.

All rights reserved, including the right to reproduce this book, or parts thereof, in any form, except for the inclusion of brief quotations in a review.

MANUFACTURED IN THE UNITED STATES OF AMERICA
KNI, INCORPORATED • ANAHEIM, CALIFORNIA

ABOUT THE AUTHORS

Dr. Simon Ramo, recipient of the Presidential Medal of Freedom, the Nation's highest civilian award, is a co-founder, the "R" of TRW Inc., one of the world's largest technological corporations and was the Chief Scientist in the development of the U.S. Intercontinental Ballistic Missile. He was Chairman of the President's Committee on Science and Technology under President Ford, a member of the Advisory Council to the Secretary of State on Science and Foreign Affairs, the White House Council on Energy Research and Development, and the National Science Board. He has received the National Medal of Science, the top national science recognition, was inducted into the Business Hall of Fame, and was the first recipient of the National Academy of Engineering's award for statesmanship in national science and technology policy. A Visiting Professor at Caltech, Dr. Ramo has been a Regent's Lecturer at the University of California, a Fellow of the Faculty of Harvard, and Chairman of the UCLA School of Medicine Planning Committee. He is the author of a number of textbooks in science, engineering, and management widely used by universities and practitioners throughout the world.

Dr. Robin K. St.Clair is a systems integrator with nearly 20 years at TRW. She has applied her systems integration skills to projects as varied as the ICBM program, arms control, the Department of Energy's Civilian Radioactive Waste Management program, and most recently the Integrated Justice System for the Republic of South Africa. She received her Ph.D. in International Relations from the University of Southern California.

CHAPTER I

The Technological World

THIS is a time of awareness that science and technology are changing the world rapidly and that scientific discovery and technological development present potential powers even greater than those that have already so profoundly influenced our way of life. It is also a time when the typical citizen demands more be done about a growing list of serious shortcomings of society. It is not surprising, then, to ask whether we can connect the potency the scientific approach is felt to possess with the need for a superior attack on our unsolved problems. Why do we not make full application of science and technology to seek corrections of ills? Indeed, many requirements—urban development and redevelopment, rapid transit in our cities, medical care, educational systems, air traffic control, depollution of the air and water ways, crime prevention—clearly are seen to have foundations in the rapid changes in society brought on by technological advances.

Now it happens that in recent years an approach has been evolving that may be described as an intellectual discipline for mobilizing science and technology to attack complex, large-scale problems in an objective, logical, complete, and thoroughly professional way. Called the "Systems Approach," it depends upon use of a

THE TECHNOLOGICAL WORLD

team of cooperating experts in both the technological and non-technological aspects of the problem to be analyzed. It starts by definition of goals and ends with a description of a harmonious, optimum ensemble of the required humans and machines with such a corollary network of flow of information and materials as will cause this system to operate to solve the problem and fill the need. The approach includes use of sophisticated techniques for assembling and processing the necessary data, comparing alternative approaches as to their relative benefits and shortcomings, making sensible compromises, producing quantitative analyses and predictions where they are appropriate, seeking out judgments from experience of the past, and introducing creative innovations where they are indicated. Resting in part on the computer to assist in weighing facts and studying relationships, the systems approach is an extended, somewhat worldly-wise and automated, common sense. It is more especially a reasoned and integrated, rather than a fragmentary, look at problems. It seeks to push confusion and hit-or-miss decision-making into the background. It leans heavily on rational, concrete judgments.

The systems approach has beginnings far back in history. But as modern systems analysis has broadened, it has already begun to be controversial and misunderstood. The systems approach has quickly attracted overly zealous proponents and, as often, misinformed detractors. Substantial disagreement exists among the professionals as to how useful the approach is for the

THE TECHNOLOGICAL WORLD

bigger problems of society, or for smaller ones when they are more "social" than "technological." This confuses the nonprofessional as to what the approach really is. It impedes its appropriate application.

Some hail it as magic, a new all-powerful tool that can demolish any tough problem, engineering or human. Of course, there are always the doubters, the mentally lazy or ignorant who are annoyed with the entry of something new. And there are some aerospace engineers who have used the systems approach but only for narrow problems in their specialized field. They often do not realize they must extend their team capabilities considerably to handle complex social-engineering problems.

Some experienced systems engineers go to the other extreme, certain the discipline is inappropriate for "people" problems. In this viewpoint, they are sometimes joined by experts schooled in the more unpredictable behavior of man. Some of these more socially trained individuals are concerned that the systems approach's disciplines cannot be applied successfully to the real-life problems of the human aspects of our civilization.

But such views are based on unnecessarily limited definitions of the systems approach. Perhaps the systems concept "in the small" matches up only with specialized engineering problems where the computer is a powerful aid. But the systems approach "in the large" includes an emphatic reliance on consideration of the often controlling qualitative factors and for judgment and intuition and experiences that are not quantifiable. Some

THE TECHNOLOGICAL WORLD

aspects of the systems approach borrow heavily from the technological methods to which the term "systems engineering" applies. But a properly carried-through systems design for a more complex social-engineering matter, if handled by a team that includes the social specialists as well as the mathematicians, will not inevitably yield useless computer-based proposals. It will not result in systems elegantly described by a deluge of numbers containing many, many digits but with neglect of the human factor.

After all, we all want our urban problems and traffic jams and smog, medical care, and educational-system difficulties dealt with not in emotional, crisis, chaotic, piecemeal fashion—which we must admit is our typical approach. We want these and other "human" problems approached by the careful setting down of clear goals, the articulating of available alternatives, and the pitting of conceivable candidate solutions against equally carefully laid out criteria. All of this is basic to the systems approach.

Is the systems approach "in the large" no more than just doing things right instead of wrong, being intelligent rather than stupid, being objective rather than irrational in approaching problems? The systems approach is that, but it is also more. We shall not in practice be able to tackle tough social-engineering problems in the "right way" unless we set up, full force, to go after the solution with all the intellectual disciplines we can muster, technological and social. So, more particularly, the systems approach is doing it right in a full fledged

THE TECHNOLOGICAL WORLD

professional way, with a deliberate, skilled effort to utilize experience, talent, and conceptual tools as well as all of the facts and the mechanical aids, like the computer.

Assuming no professional preparation on the part of the reader, this book discusses how a systems expert goes about analyzing a problem, designing and evaluating answers, simulating, and predicting results of alternative proposals, and does these things through the use of techniques which must be called professional because they can only be done well by people who prepare themselves well and build up experiences in the approach. The systems approach, expertly applied should yield us an increasing ability to make better decisions in the use of our resources, choose proper options in the way we design our cities, transportation systems, communication networks, educational and medical facilities, waste-disposal techniques, crime-prevention methods, and others. We shall gain more for our expenditures of resources and human energy.

The systems approach will not solve substantial problems overnight, nor will it ever solve all of them. No matter how broadly skillful is the systems team, the approach is no more than a tool. It will never give us something for nothing, or point the way to an ideal organization of all society, or lead to the planning and production of all of the products of society so as to satisfy all. It will not change the nature of man. It will provide, that is, no miracles. All it can do is help to

THE TECHNOLOGICAL WORLD

achieve orderly, timely, and rational designs and decisions.

But this "minimum" is something very important. So severe are some of our problems today that chaos threatens. The systems approach to the analysis and design of anything—from a traffic management system to a new city, from a regional medical clinic to a full hospital and medical center, from an automated fingerprint identification system to a fully integrated criminal justice system—will provide no facility of infinite capacity. But it will lead us to designs and operations that will at least not be chaotic. The systems approach, if it is used wisely, is, at the least, a cure for chaos.

The world society of today is already a highly technological one, but our future will be even more influenced than has been our past by scientific breakthroughs and technological advances. The steering of our civilization's course appears now to be coming not alone from expressed human needs. It is equally, or maybe even predominantly, from the expansion of our technology. So rapid has been the pace of technological change that we can see about us, alongside the benefits, numerous penalties of our failure to provide adequate social changes equally rapidly.

The world is a paradox of technological progressiveness and social primitivism. For several decades we have had the technological capability to destroy civilization in a few minutes, so great and quick is the nuclear energy we can release. But during this time we have been unable to

THE TECHNOLOGICAL WORLD

build a sociopolitical system to preclude this from being a serious threat. An unsophisticated observer from a less advanced planet might expect that, with so tremendously powerful a force in our possession, we could and would employ it with high priority for peaceful uses. Nuclear scientists have told us—years ago, in fact—that by the controlled release of nuclear energy we could move mountains, change the course of rivers, ultimately even influence weather and generally make the earth's surface and its total resources more readily available for this planet's inhabitants. We have been unable, for social and political reasons, to arrange for more than a preliminary, token effort in these directions.

Technologically, we are a "three-dimensional" society. We have developed the means to survey and utilize the vast space around the earth. Listed among the benefits are improved global telephonic and television communications; better navigation and traffic control for the airlines; more economical transmission of needed data to keep the world's business and industrial operations going, including computer-to-computer transmissions; and much superior examination and study of the earth's surface for the discovery and mapping of the resources of the earth for their more efficient use. This does not count the benefits that we have no way of proving will come, but that we have every right from past experience to expect, out of new scientific discoveries as we probe an unknown frontier.

While the benefits of the technological advances brought about by the space program are indisputable, the

THE TECHNOLOGICAL WORLD

origins were motivated by different forces. The size, timing, and particular makeup of the U.S. space program as it began was more especially determined not by potential civil benefits, but rather by a commitment to a prestige race, a "Science Olympics," in which the U.S. felt it was important to beat a rival nation, the then USSR, at all costs.

Consider another dilemma that demonstrates sociological immaturity. We are on the threshold of fundamental breakthroughs in the field of biology. We are cracking the genetic code to unlock the basic secrets of the life process and reveal the distinction between a living molecule and an inanimate one. This augurs well for our ability eventually to eliminate disease and greatly improve longevity. At the same time, we are perplexed and frustrated by a relatively simple biological problem: that of controlling the population explosion. We have the scientific knowledge to handle this problem, but we do not have the social wisdom to put this knowledge to work.

In our wonderful age of technology, we have learned how to extend the human intellect with electronics. We know how to create a powerful teaming of man's brains with electronic devices to make possible the quick and accurate handling of most of the information needed to be accumulated, stored, processed, and communicated so as to control the physical operations of the world. In the professions and in education, informational and intellectual tasks can be handled with new capacity and new speed by people using computers to assist them.

THE TECHNOLOGICAL WORLD

This is making it possible to provide for most of man's material needs and comforts much more efficiently. This partnership with the computer is replacing homo sapiens alone in the handling of all of the information that "makes the world go round." But the social dislocations that will result as humans share the world with computers are justifiably to be feared.

Technology has increased the standard of living of much of the world and can do so readily for the rest. It has made the world smaller by advancing communication and transportation, and can yield even more benefits in every facet of our activities. However, it is beginning to be more apparent every day that technology has not been used to the fullest to improve our society and minimize its shortcomings and ills. Furthermore, technological advance unaccompanied by appropriate social advance has had sociological effects we are not dealing with adequately. It is not that our social progress is absent. Significant advance can be found. It is just that, compared with the need, it falls far short.

Now, there are two categories in which the current application of technology to the needs of society is relatively healthy and productive. One such example is the free-enterprise, free market sector. For much of what technology can do for our society, private capital can readily plant the seeds and grow the fruits. The resulting products are based on a correlation between the capabilities of technological industry and the needs of society. The competitive market and the profit incentive bring together the demand for the product, on the one

THE TECHNOLOGICAL WORLD

hand, with the resources and know-how to get it developed, produced, and distributed, on the other. This system is far from perfect, and it does not cover everything. But it works well in causing society to be served by a substantial portion of the large potential of science and technology.

The second area in which the application of science to society has become well established is that which involves national security. When there is an acknowledged need for action to ensure group survival, and when the products of technology required for such purposes do not flow out of our free-enterprise system as a normal "peacetime" pursuit, then we have learned how to marshal our technological resources under government sponsorship. In this way, nations produce highly complex defense systems. Here again, the processes leave much to be desired. But, if we have not learned how to operate truly efficiently, at least a well-established government-industry relationship exists to produce the equipment needed to safeguard the nations.

A large segment of national need and endeavor remains where technology has hardly been brought to bear. Yet this "third" area is one where technology and science could well contribute improved solutions. At least it can be said that without a superior approach good solutions are certainly not likely to be forthcoming. Examples here include control and utilization of natural resources, rapid transit in our cities, emergency response systems, air and water-pollution control, city development and

THE TECHNOLOGICAL WORLD

redevelopment, and improvement of our educational and medical facilities, to name just a few.

These systems, which we shall call "civil systems," tend to have certain common characteristics: They are typically large and complex. The solutions that are indicated (when they are) appear to be extremely expensive to implement, and they typically require the use of sophisticated technology. Doing something substantial about the problem is impossible unless we satisfy, and obtain the cooperation of, many semi-autonomous groups not accustomed to joining up to work together. The problems generally cannot be solved by the development of a single product or service. Instead, what is involved is an interacting arrangement of people and things, with concomitant matériel and information flow, in configurations and installations for which there is little precedent. New concepts, new apparatus, novel functions for people, untried interconnections among them—all are needed. Moreover, the whole complex of sub-elements usually constitute a system that represents a considerable deviation from the present and historic method of doing these things.

Even the first step in establishing a group that can delve into these problems and come up with practical, meaningful proposals is difficult. This alone usually requires new arrangements of society. Moreover, even if good analytical planning has been done, it is difficult to arrange an operational structure to provide the resources, authority, responsibility, and funding to implement the solution.

THE TECHNOLOGICAL WORLD

These civil-systems problems do not lend themselves to quick and complete solution by private enterprise. For the private sector to furnish the answer there needs to be some kind of "customer" organization, some grouping of the people/users into a family of buyers. Take air pollution in a large urban area. Who will pay for a program to identify and develop specific pieces of equipment to go into industry, homes, and automobiles to eliminate a regional smog problem? Who will direct and force the development, and how? In short, where is the market? The relationship between specific products to be produced by industry and our way of life must be established somehow, somewhere. It must come partially by citizen understanding and the awareness of its leadership. After this is achieved, special legislation must follow.

Such a working out has taken place with regard to the defense establishment of the United States. The U.S. Defense Department is a huge bureaucracy. Still, it presents virtually a single dimension to industry seeking to provide it with its stated requirements: its weapons systems. By now this has become a classical relationship of a buyer with funds and needs and of suppliers with resources and capabilities set up to sell to that buyer. It is straightforward as compared, for instance, with the complex and chaotic situation of the Los Angeles City transportation problem. Here no honest-to-goodness customer-to-supplier relationship exists. Nor have the needs been adequately defined for solid action. No group can be said to be in a fully accepted position to define

THE TECHNOLOGICAL WORLD

these needs, command the funds, and assume the responsibility for implementation and operation. Added to this lack of designated authority is the confusion caused by many independent groups pulling for this or that approach to rapid transit; and superimposed upon this is the dynamics of the area's rapid growth, which is intensifying the problem daily.

The foregoing shows the pessimistic side of the situation as it exists today. There is also an optimistic side. If a history of the application of science and technology to the problems of society is written a hundred years from now, 2000 may well be cited as the year in which a noticeable and important tilt began to take place in the balancing of technological and social advance.

Why can this be said? For one thing, we are seeing now a birth of understanding by the citizens. The needs of society and the power of technology to do something about these needs are being articulated daily with increasing clarity.

Thinking people who live or work in those cities that suffer from the universal problems are asking: If we can give an astronaut good air to breathe in a space station, then why not in our cities? If our technology permits us to fly supersonically from North America to Europe in a couple of hours, then why cannot we apply that technology to the end of getting us to the airport in less than that time? If we have such control over the release of tremendous amounts of energy that we could readily destroy society, then why can we not use this energy

THE TECHNOLOGICAL WORLD

source to desalt the nearby ocean waters and eliminate city water crises? If we can record the heartbeat of an astronaut ten thousand miles above the earth, then why can we not readily provide superb medical monitoring for the bed patients of our hospitals? If we can provide a multibillion-dollar system to gently place a vehicle on the surface of Mars, with the associated computers and software, video imaging and data collection systems, then why can we not design and build properly laid out cities?

Thinking voters recognize the budgetary burdens on governments at all levels. They realize that these civil problems are complex combinations of many social, psychological, emotional, cultural, and economic factors with technological facets. We do not have the time to head in grossly wrong directions looking for solutions, then to halt and start over. The problems over all seem to involve numerous interconnections. Thus, social problems are connected with city problems, with poverty and unemployment, and with lack of education for the jobs our technological society needs to fill. The public, its spokesmen in government, the industry leaders, the academic fraternity—all want to attack these problems, but at the same time all realize that the problems are very, very difficult to solve. Everyone knows we need all the logical and creative tools we can possibly mobilize to seek the solutions.

Meanwhile, side by side with this growth of interest and concern by the citizens, something pertinent has been happening on the technological front, the

THE TECHNOLOGICAL WORLD

development and application of a powerful methodology—the systems approach. An essential ingredient in the successful application of science to military and space systems, it is beginning now to be recognized that the systems approach can also be made well suited to attacking civil-systems' problems. In essence, the systems approach is being seen as a unifying, integrating mechanism for application to social problems. In the next chapter we shall describe the nature of this methodology.

CHAPTER II

Systems—Something Old, Something New

IN the systems approach, concentration is on the analysis and design of the whole, as distinct from total focus on the components or the parts. The approach insists upon looking at a problem in its entirety, taking into account all the facets, all the intertwined parameters. It seeks to understand how they interact with one another and how they can be brought into proper relationship for the optimum solution of the problem. The systems approach relates the technology to the need, the social to the technological aspects. It starts by asking exactly what the problem is and what criteria should dominate the solution and lead to evaluating of alternative avenues. As the end result, the approach looks for a detailed description of a specified combination of people and apparatus—with such concomitant assignment of function, designated use of matériel, and pattern of information flow that the whole system represents a compatible, optimum, interconnected ensemble yielding the operating performance desired.

The systems approach is the application of logic and common sense resting on a sound foundation. It is quantitative and objective. It makes possible the consideration of all needed data, requirements, and (often conflicting) factors that usually constitute the heart of a complex, real-life problem. It recognizes the

SYSTEMS—SOMETHING OLD, SOMETHING NEW

need for carefully worked out compromises, tradeoffs among the competing issues (such as time versus cost). It provides for simulation and modeling so as to make possible the predicting of performance before the entire system is brought into being. It makes feasible the selection of the best approach from the many alternatives.

Having said all these strong things about it, we must hasten now to say also that the systems approach is not really a completely and basically new concept. It is not a mystery. It would be an overstatement to describe it as a completely novel intellectual discipline. Surely the word "systems" as we are using it here is familiar to us. We have known it in "telephone systems," "electrical power and distribution systems," "transportation systems," "Federal Reserve Systems," and "military weapons systems." The word "systems" connotes the whole, the combination of many parts, a grouping of humans and machines, the assembling together of components or subsystems to accomplish a task. By itself, this is an old concept.

The notion that to attack a large problem effectively it should be done in an organized way to attain maximum success is even older. When the Sphinx was built, and the Roman roads and London Bridge and the Panama Canal and the New York subways, in every instance a team was assigned. Its professional job was to relate the technology to the objectives, the social environment, the available resources, the time constraints, and the economics. It was the team's responsibility to consider

SYSTEMS—SOMETHING OLD, SOMETHING NEW

the project in relation to the society it must serve and to recognize that there were an infinite number of detailed routes to completing the task. Similarly, the telephone system in the United States and electrical-power-distribution systems did not come into being by the random adventitious dropping from the sky of pieces of apparatus that just happened to work well when connected together.

Behind all of these systems were groups of system analysts and system designers. They must have understood that they would not realize a good system design unless they were very clear about the goals. They must have sought criteria against which they judged alternatives. Their sponsors, governmental or private units, also must have appreciated the need for a practical, implementable systems design in some sensible relationship to the existing society that called for the solution and that would judge the result.

Of course, in basic principle terms, you don't have to be a "professional" to use a "systems" approach. When any one of us has a problem of any kind—preparing a household budget, choosing where to live, what job to seek, designing a chair, producing neckties, building a house, or selecting a route to take on a trip—in every instance, it is well to be logical, to use common sense, to consider objectively all the factors involved in choosing a solution. It should be realized that there usually are many alternatives to reaching any objective, and a "best" way only if you can be clear enough about goals and criteria. In this sense, then, the systems approach is old

SYSTEMS—SOMETHING OLD, SOMETHING NEW

indeed. But if the problem is simple to understand and the candidate solutions are easy to identify, optimize and compare, then the concept of the systems approach is in the background. That approach would mean merely the use of logic and common sense. A systems approach would not then involve the assembly of a large team of interdisciplinary experts and the formal execution of a powerful, quantitative listing and analysis of every potential solution.

What makes the systems approach now appear new? What makes it justified and significant to talk about it today as a "mobilizing" technology that is ready for application to the big civil-systems problems of our times? Partly it is because of the great recent acceleration of the development of the tools of systems engineering. Some of this in turn has resulted from the need for this methodology in the highly complex and costly defense and space programs. It is also the consequence of the expansion of the technological aspects of our society, dealing with which has justified large-scale advances in the techniques of the systems approach.

As compared with a few decades ago, a substantially greater number of professionals exist today who are well seasoned in interdisciplinary problems. They know how to relate the many facets of one technology to another and to relate these in turn to all the non-technological factors that characterize practical problems. They are "systems engineers." This is appropriate if the word "engineer" is used in what probably should be its true

SYSTEMS—SOMETHING OLD, SOMETHING NEW

meaning but which, when applied to the work most engineers do, is too broad. Engineering is generally defined by the dictionary and by members of the profession as the application of science and technology to the needs of society. Most engineers, however, are specialists in a particular branch of science or technology. To be professional in the overall application of science to society, some of the group must know society well. Such qualifications are essential for the competent systems-engineering team. Granted, this is an age of specialization, and a good systems-engineering team will include many individual specialists who have learned how to work their areas into sensible interfaces with the contributions of the other specialists. It is the team that must include the total intelligence, background, experience, wisdom, and creative ability to cover all aspects of the problem of applying science and technology, and particularly, who must integrate the overall intelligence—as we stress in this book, who must mobilize it—to reach real-life solutions to real-life problems.

A good systems-engineering team combines individuals who have specialized variously in mathematics, physics, chemistry, biology, other branches of physical science, the many branches of engineering, economics, political science, psychology, sociology, business finance, government, and so on. The systems engineering team attacks the interaction problems among these specialties that characterize any practical problem. This is worth stressing because it is quite often assumed that narrowly

SYSTEMS—SOMETHING OLD, SOMETHING NEW

conditioned engineers skillful in the details of technology, but with no knowledge of people and the workings of our social systems, are brought in to apply a “systems” approach to revolutionize these systems. It is assumed that they do this by putting all of the facts on a computer and causing the computer to come up with a perfect answer, or by some other "technology-pure" approach that disregards the human elements. That concept of the systems approach is erroneous.

The systems approach then, as we shall use the term, implies much more than technology. It leans on interdisciplinary teams. "Interdisciplinary" are "generalists" who can bring together the skills and contributions of the specialists and create a unifying and integrating team.

New tools are coming forth rapidly now to make the systems engineer more effective. Computers available now make possible the handling of the information basic to quantitative optimization-seeking analyses. The typical civil systems problems needing solutions today are of great scope. The amount of data and the complexity of the involved interactions are staggering. To organize such problems one has to rely on sophisticated, highly trained individuals who, despite the confusing avalanche of issues to consider, have learned to be objective, logical, complete, and quantitative. With the computer to aid them, they are now able to make detailed analyses of candidate solutions in a reasonable period of time that would have been absurdly out of the question a decade or two ago.

SYSTEMS—SOMETHING OLD, SOMETHING NEW

Is it worthwhile to mobilize expertise and scientific and technological talents and tools in an effort to perform better? Within less than a decade the United States shall substantially exceed a ten-trillion dollar gross national product. This means that during the first decade of the next century the overall price of all the products and services bought in the U.S.A. will be 100 trillion dollars, give or take a few trillion. Fully 10 percent of that total, 10 trillion, will represent effort in just those fields that we have mentioned above under the title "civil systems," like transportation, urban development, information systems, public safety and criminal justice systems, water- and air-pollution control, new medical and educational facilities, environmental protection, and others. The true value to our society of this 10 trillion dollars' worth of expenditures can be altered greatly, depending upon whether or not the efforts are properly chosen and conceived, well organized, and efficiently operated. The application of the scientific method and technology to the proper extent, and this is what the systems approach seeks to effect, can greatly enhance the value of the work performed. The costs of applying the systems approach will be a small part of the added worth that its successful application should bring. We are discussing not a small icing on a cake but, rather, the choice of main ingredients and the way to bake so as to make the cake taste good, cost less, and be highly nutritious and easily digestible.

CHAPTER III

In Contrast, the "Piecemeal" Approach

LET us try now to understand more about the nature of the mobilizing methodology called the systems approach. Let us take some familiar complex systems and contrast the solutions arrived at when a "piecemeal," random, or disorganized approach is used as compared with applying a systems approach.

The word "systems" is especially familiar in connection with the "telephone system" around which so much of our business and social communication revolves. The telephone network in the United States is an example of the development of a great resource which has been designed, built, and operated as a system. Due regard was given to the relationship of the whole to the components, of the goals to the alternatives, and of the technology to the economic and human factors. Try to imagine the telephone service we might have had if it grew not through careful, creative, and sound systems design. It is not easy to do this imagining. System design excellence is so characteristic of the telephone service in the United States that we take for granted the details that have been so competently arranged to serve us. Maybe the reader believes that it is far from perfect. But, consider. The telephone system is not just the instrument we hold in our hands. It is a closely integrated network of humans and equipment, stretching for thousands of

IN CONTRAST, THE “PIECEMEAL APPROACH”

miles, arranged so as to make possible interconnection between any two points in the vast system. The design is highly integrated and includes manufacturing, installation, repair, training, phone books, billing, cables, satellites, emergency services, coin pay phones, switching stations, conference calls, and FAXes.

It had to be developed as an integrated system. It simply could not have been created otherwise and worked as well as it does. What would have happened instead, would not have been a telephone service similar to today's, only somewhat lower in performance. Instead it hardly would have worked at all! It would not be the foundation for business, social activities, government, transportation, and so many other key communications elements of our society. This point is easier to elaborate on if we shift the discussion momentarily from the telephone system to one equally familiar, which was not ever designed as a system. This is personal transportation by automobile.

The personal automobile transportation "system" of the nation is, of course, more than the vehicle itself. It is roads, spare parts supply, gasoline production and distribution, traffic lights, drivers' licensing, casualty insurance, parking lots, speeding tickets, smog, and much more. Without these subsystems, without attention to the necessary elements, the overall system could hardly operate. But it was not thought out and designed as an integrated system from the beginning. It just grew. Its many interacting factors worked themselves out (only partially) in the “school of hard knocks” of

IN CONTRAST, THE "PIECEMEAL APPROACH"

incompatibility, compromise, and considerable chaos, a process that continues today when we have reached the level of hundreds of millions of operating automobiles.

This system, resulting from a piecemeal, uncoordinated, approach, is seen now to possess many ills. These stem from the failure to design an integrated combination in which all the factors were properly considered in relationship to one another from the very inception. Thus, while the "subsystem" consisting of the vehicle itself may be superbly engineered by the automobile manufacturer to please the public, no coordinating team has responsibility for the design of the overall system of which the automobile is but a component. Hence, our cars are not well suited for the city driving for which most of them are actually used most of the time, and we should not, as some do, blame the manufacturer of the car. Automobiles capable of doing a hundred miles an hour, and allowed to do sixty or seventy legally on most of the highways of the nation, are instead most often crawling at speeds in our cities that freeze them into mass congestion. This wastes millions upon millions of man-hours daily, saps the nervous energy of the drivers, and defiles the air we breathe. Furthermore, tens of millions of people have been killed or maimed by automobile collisions, grim proof that the total system is not right. The federal government has actually entered into the design of cars, unthinkable when the automobile system was first beginning to develop.

We suspect that if the personal-automobile system could have been designed as a system, with the objective

IN CONTRAST, THE "PIECEMEAL APPROACH"

of furnishing the most satisfactory answer to the requirement for personal transportation in our cities, we would save not only time and money, but many of the lives lost in accidents. To those of us who live in highly populated areas and must make our way from home to work in an automobile, it seems now quite certain that the personal automobile should not be considered in isolation. Its design must relate properly to mass rapid transit and other aspects of overall city design. Furthermore, the relationships must start with goals: What are we trying to accomplish with this transportation system?

The piecemeal approach, the random, casual, ad-libbed bringing of the personal automobile into every day life, was adequate for many years. In a way, the systems design could be handled in an extemporizing manner for a while. Some roads and many streets already existed as a beginning, because we had horses and pedestrians. The garages and gasoline and spare parts could come along gradually, led by the market's supply -and- demand forces and their interplay. We had the time, had we been a little more alert, to apply systems concepts, to use logic, objectivity, and quantitative reasoning early so as to anticipate problems that have developed and handle them ahead of time. We could have seen the growing traffic and mass transportation needs of our cities, and the smog and safety hazards. In principle, at least (although apparently not in practice because of our social immaturity) we could have applied economic, social, and technological analysis and arranged some

IN CONTRAST, THE "PIECEMEAL APPROACH"

superior way to have people move about during their working or playing day. But we didn't plan ahead. Now the problem is truly tremendous. A very complicated mismatch exists of uncoordinated, independently led aspects overlapping in such a way that to straighten out the problem seems almost impossible. It is like knitting with a tangled ball of yarn. It must be untangled before we try again to make the sweater.

Let us now return to the telephone system as it developed in the United States, and force ourselves to imagine that somehow the invention of Alexander Graham Bell, through a series of cumulative oversights, incompetence, or perhaps accidental, wrong decisions, grew up in a kind of helter-skelter fashion. If this had happened, we would still be able to make a long-distance call, but only occasionally and with great difficulty, to certain highly restricted places, rarely hearing well. (In just the same speculative way, you can get across Manhattan by car on a busy day painfully, or sometimes find a parking place near where you are going in any crowded city, or get in and out of a big city airport in less time than it takes the plane to go between principal cities).

Starting our telephone system imaginings from the beginning, suppose the phone has just been invented. Some enterprising manufacturer starts making telephone instruments for your home or office in his little backyard workshop. He sells one to you. You are interested because you know that you can hire an electrician to connect your instrument to that of a friend some distance

IN CONTRAST, THE "PIECEMEAL APPROACH"

away with whom you would like occasionally to speak, or to your physician's office, or to another firm or two with whom you do business. All of this means you are quite wealthy (at least before you installed your phone). Just as the government provided and maintained roads, and automobile manufacturers never had to do so, so the city might put some "telephone" poles up along the sidewalks on some streets and leave it up to your electrician to put his wires between them. When there get to be too many wires on the pole, or the pole begins to crack and some wires fall down—well, that's no different from the roads that are already congested and sometimes under repair and with detours. In other words, sometimes your phone service will get through and sometimes not.

Of course, the first real systems question that arises is: How do you arrange to be able to talk to more than one or a few friends and business associates? To be sure, you can keep stringing up wires between yourself and all of them. Some manufacturer might offer you a switching box so that you can simply turn a dial to connect to the particular line that is calling. Of course, soon someone would notice that the number of lines that this takes constitutes the limit of the telephone service. (If you had a thousand people in an area who wanted to be able to talk to one another, each one to every other one, then you would need many, many thousands of lines going in and out of all the various houses and places of business—999 from each one, if you can picture it.) An enterprising businessman or two might risk setting up a

IN CONTRAST, THE "PIECEMEAL APPROACH"

"central station" and let everyone connect to it for a fee. He could then connect you to others with whom you might want to talk who also wire into his central station.

And so we might imagine that such central -station operations would spring up all over the country, several each in individual cities. You would need to connect into each one in your town, because you would not be sure which one your friend is connected to. Then, of course, the problem arises of connecting with each other. No one of the contributors, from the manufacturers to the connector-uppers, would have a large enough "systems staff," specialists and integrators in all of the technology and in the business and human factors, to be able to see all of the possibilities of economical interconnection and growth. Technological development would be very slow; the service would be terribly expensive. The telephone would be a minor adjunct to life in general.

Of course, you should reply that things had to start this way and that sooner or later the practical requirements of our technological society for fast, flexible, economical, reliable communication would have forced the development of the telephone service into good system practices. But the point is that the system approach was seen as necessary, whether it resulted from exceptional insight of those who had the position to influence the development of that service or from the pressures of purely pragmatic aspects of our developing society. Here is a case where we can see the systems approach as having been used, and we see the results in the important position attained by telephone service, a level of

IN CONTRAST, THE "PIECEMEAL APPROACH"

communications between individuals and businesses unthinkable without a design that was based on the whole's being an integrated complex. But there are plenty of areas of life today crying for the systems approach that have never gotten it and are not yet getting it, and where the service presently available is abominable, unreliable, unmatched to our needs, uneconomical, in some instances nonexistent. The practical requirements of our society have not yet forced us to good system practices.

Let us take an example now of a sort of half-and-half situation, where the systems approach has been used but spottily, intermittently, too little and too late, and where, as a result, we are rapidly getting ourselves into some real difficulties in a service that has become an essential part of modern life.

The air-transportation system is one. It is much more than the airplane. It is baggage, getting to the airport, blind-landing radar, air-traffic controllers, communications, maintenance crews, ticket agents, food preparation, national hookups of electronic reservation-making equipment, automobile parking, training schools, and regulatory laws. Here the systems approach has been too lightly used. The problems have not in the past been given the kind of high-quality, complete, overall systems-engineering attention that the importance, the complexity of the system, and the payoff to be realized by so doing all justify. Air transport has indeed been recognized by the leaders of the industry as a systems problem. However, it has been a nearly impossible job

IN CONTRAST, THE “PIECEMEAL APPROACH”

of organization to get government, the technological industries, the airline companies, and all the other entities involved—and there are many more—together to attack the whole as a system. The technological, sociological, and economic factors are many and puzzling. They are costly to analyze and they remain unassigned as to integrative responsibility. As a result, the overall expenditures and resources allocated to air transportation are much less effective than they could be, and becoming even less so as the volume of activity continues to accelerate faster than good systems design can be sponsored and executed.

We are not without more examples of important activities that need, but have not been favored by, the systems approach. The typical hospital is a large complex of people, equipment, matériel, and information flow. Business, logistics, accounting, and medical test data are moving about. Training and treatment coexist. Patients, interns, doctors, nurses, visitors, accountants, orderlies, medicines, towels, and X-ray machines weave in and out of a busy mountain of activity. Exceedingly sophisticated activity is intermixed with the many specialized and mundane aspects of keeping a facility involving many people and things going smoothly.

The systems approach has hardly begun to be applied to the medical center. The systems approach here would start with an attempt to set down clearly what the objectives were for the future of the center. A statistical data base would be established as to the probable spectrum of activities from the present into the future.

IN CONTRAST, THE “PIECEMEAL APPROACH”

The number of patients, kinds of illnesses to be treated, training, examinations, business and test data, and visitor handling would be estimated and listed. What the hospital would expect to have to do and what equipment and installations it should possess to do it with would be set down carefully. Flow diagrams would be set up to show the movement of people—physicians, nurses, clerical staff, patients, and others—and the type and flow of information and of items like clinical patient records, medicines, X-ray films, foods, etc. New technology affecting medical care would be considered. Comparative, economic, and performance analyses would be made of alternative ways of treating patients, location of ambulatory and acute care facilities, layout of the hospital and of modes of operation. The information required and the functions of all the people would be carefully examined.

We shall, in a later chapter, look more particularly at hospital design as an example of the way the systems approach applies to such a problem. For the moment it is sufficient to observe how beneficial it ought to be really to have a sophisticated team go out and get the facts, know how to handle them logically and quantitatively, and apply themselves to seeking to understand the relationships amongst the many interlocking parameters, the many variable functions that describe and determine the workings of the operations. A good systems organization would not rest until it had, in effect, pictured in great detail how the whole system would operate under candidate plans differing as to investment

IN CONTRAST, THE “PIECEMEAL APPROACH”

in new technology, assignment of roles and missions of all people and equipment, and physical layout. They would set out to optimize the quality of medical care from the stand point of the patient within available physical resources, people, time, funds, and new technology.

We have only to add at this point, before leaving the hospital example, that all of us who have been in the hospital can readily observe, if we are not overly drugged at the time, that a piecemeal rather than systems approach leads to numerous problems: delays, inefficiencies, slow information transfer, high cost, over-congestion, unreliability, and consequently, poor medical care. It is clearly an example where competent systems analyses should pay off.

CHAPTER IV

The Systems Approach or Chaos

LET one good musician be told to play whatever comes into his mind, and at worst you may hear something you do not care to listen to. If your tastes happen to agree, you probably will find his performance enjoyable. But ask each of one hundred excellent musicians in an orchestra to go about choosing notes in complete disregard of the others and the overall result will be musical mayhem. It is not a desire for efficiency, time-saving, or economy that causes us to prefer harmony in the ensemble of the musicians rather than noise. In the previous chapter, we introduced some of the characteristics of the systems approach and contrasted that approach with its antithesis, an uncoordinated, piecemeal development. We indicated that the systems approach would save time and money because an operation designed as an integrated, optimum arrangement of components would be more satisfactory in every way than one where things just happened.

In this chapter we want to make an even stronger argument for the systems approach as applied to many important societal needs. In many important problems of our society our choice now is clear: Either we approach them zealously, combining science and practical common sense, or we risk absolute and utter confusion and chaos. It simply will not do at all to let the problem

THE SYSTEMS APPROACH OR CHAOS

build up, to let the operation remain a group of uncoordinated elements, feeling that the only penalty we incur is a tolerable deviation from optimum. In some situations you cannot have a less-than-good system. If you ignore the need for compatibility and harmony in the ensemble, if you fail to ensure the appropriate kind of interactions—in short, if you do not work the problem as the system problem that it really is—then you will have an absolute failure, not merely an inefficient compromise.

Let us take some true-to-life examples of situations where a coordinated approach considering all elements is necessary because the alternative leads to total breakdown.

If you are a frequent air traveler to the world's principal cities, you know how close we sometimes seem to come to a complete system collapse. A slight increase in the magnitude of the basic operating variables—numbers of passengers, numbers of planes trying to land, amount of baggage to be handled, amount of paperwork at the ticket counter required—and the badly belabored system is threatened with paralysis. People, planning for months for a holiday trip and allowing a most generous amount of time to get to the airport, may miss their plane because of a sudden, record congestion in automobile traffic on the way to the terminal. Less rare is the one-hour landing delay after a fifty-minute flight between two cities because the rate of arrival of planes is too high for the facilities below. Such things do happen. And, when they do, the individuals who become

THE SYSTEMS APPROACH OR CHAOS

involved have reason to understand what is meant when we say that it is beyond reason now to allow this air-transport system to continue to grow as it has. As speeds and the number of planes and travelers and tons of freight increase, control of the timing of each event becomes more critical. The number of items that have to be brought into consistent alignment—the flight information, the instantaneous position and speeds of planes in the air, the flow of people, the equipment, the spare parts, the controlling information—increases, and everything must be closer to being at the right place at the right time, or the system will not just become less efficient; it will come to a halt.

A bridge that spans a river is still a bridge even if it is poorly designed, shaky when traversed, liable to collapse any moment, and less useful than was hoped because it must be confined to smaller loads than would be desirable. It would be rated as an inadequate design, perhaps, but still rated as a bridge. Similarly, any time we assemble people and things and arrange for them to go about performing a task, we have "designed" a system. It may be an abysmally inferior system. The system's engineering may be rated as of low quality, in some instances hardly recognizable as engineering. But it is still a system.

As with the bridge, our inferior system may sometimes be relatively simple. The number of its parts may be small. The relationship between its performance and the specific functions of the people and machines involved may be so readily understandable that a reasonably

THE SYSTEMS APPROACH OR CHAOS

acceptable system may be assembled with little thought. If there are not too many pieces and sophisticated interactions among them, then the system that the whole ensemble constitutes may be far from an optimum designed one and yet still render us some service—not good, but also not zero. As judged against reasonable criteria, the system design may be full of shortcomings, but a complete breakdown does not necessarily have to threaten. We simply adjust to the use of the system with its poor performance.

Sometimes this is the situation in air transportation. In a small city, with a small amount of air traffic, one does not worry about traffic jams to and from the airport or about too many planes in the sky at the same time all wanting to land. When a certain level of activity is reached, however, the interactions of these and many other factors begin to be important, finally dominant. Press the system further, and it falls below the threshold of workable compatibility. As we shall see in a moment, the breakdown occurs because each of the strained subelements that make up the system—people, equipment, information, and matériel flow—reacts by putting an excess burden on the other and connecting elements. The reaction to this excess burden is higher pressure on the system's components, and the reaction inexorably builds to a point of runaway and collapse.

Suppose a plane arrives one-half hour late for one reason or another. In a simple system, the un-crowded airport, passengers, and luggage all adjust to the situation. There is some dislocation, inconvenience, loss

THE SYSTEMS APPROACH OR CHAOS

of time, reduction in efficiency, and added cost. But no effects build up and up to a breakdown. In contrast, in a situation close to a threshold, a compounding effect sets in. With the delayed flight having missed its tight schedule for positioning in the traffic pattern, the landing, deplaning, and refueling cycle is whip-lashed out of kilter. It is now difficult and, in the extreme case, almost impossible to take care of that plane. When all the actions on that flight are finally handled, other flights automatically are delayed. In particular, the next flight of that same plane takes off hours late, though its actual delay in landing was only one-half hour. The maintenance crew preparing the late plane for its next takeoff could not handle it when it arrived late. They were already scheduled to service another. The Yo-Yo effect is now getting into full swing. Passengers discovering a delay of their flight decide to shift to a competitive flight. The ability of passengers to meet connecting flights is threatened and often impossible. The airline reservation-making apparatus at the counter is jammed, interfering with the handling of passengers on another flight about to take off, causing it to be delayed. The baggage people are busy trying to get back bags already checked in.

It is like a dog's sudden appearance on a freeway, which forces the first driver to put his brakes on suddenly, and driver number two, even if he is not following very closely, is required to be even faster in response with his braking to keep from ramming car number one. Driver number three behind is caught with an even greater

THE SYSTEMS APPROACH OR CHAOS

challenge, and drivers number four, five, six, and seven simply don't have a chance. The result, to misuse a nuclear term slightly, is a critical pile -up.

A question naturally arises. Could not this kind of runaway congestion, which brings the system down to a virtual halt, have been averted by ample safety factors in the system design? Just as the cars on the highway should not follow so closely, we should not schedule things so tightly in the operation of the air -transportation system. It is difficult to arrange that the cars do not follow closely if we have to handle great peaks of traffic within reasonable cost for the highway. We cannot snap our fingers and create more parallel lanes. But in the case of the air-transport system we have to add something much more significant and to the point. In that situation, there are so many overlapping parameters that the system can easily be close to saturation in actual operation even if there appears to be lots of surplus capacity. Unless a careful, creative, sound, and thorough job is done of anticipating and working out optimum relationships, it can be generously designed in many aspects and still have no real reserve.

We want to have enough surplus handling capacity in the air pattern over the airport so that a plane coming in late can be fitted in with ease. Similarly, we would like enough handling capacity on the ground to serve a plane arriving out of its scheduled time. But if we are going to have all this excess capacity to take care of the sharp peaks, then we must expect deep valleys in which the facilities will be used only lightly and in which much of

THE SYSTEMS APPROACH OR CHAOS

the expensive manpower will be idle a good deal of the time. More importantly, we will have to limit greatly the amount of traffic we are willing to handle into that airport. This will call for building many more airports or else changing our concepts of the system.

Such concepts might include government rulings to add lower price incentives for travelers to use flights during off hours. Or, we might consider increasing the extent of use of electronic techniques for handling all the information that controls the flight of airplanes and by this means to reach such optimum detailed scheduling as will increase the usefulness of a given investment in facilities and manpower. It means, of course, that there would have to be some very competent statistical analyses made of the frequency of different kinds of situations. Quantitative evaluations would have to be placed on alternatives within a broad spectrum of different ways of handling emergencies and other deviations from average. This is applying the systems approach.

Air transportation in the world has reached the point where it is rare to be able to accept casual systems design. The many determining factors that make up the total operation cannot be considered as independent. The avoidance of chaos and breakdown by building luxuriously high over-capacity is precluded, not only by cost, but by the way cities happen to be laid out, how populations happen to live, and how the society is geared now to air travel. Air-transport problems must be looked at in their entirety. All the elements must be accorded all

THE SYSTEMS APPROACH OR CHAOS

the necessary dignity, weight, and attention, individually and together, so that a consistent, logical system will evolve. This has to be the approach from now on if we are not to have grand confusion in our air -transport system. Numerous groups, each having only a part of the responsibility, competence, and authority to influence the systems design of air transport must somehow be brought together to work this problem out. Those who control vehicle design and air traffic, make rules about the safety of the air, allocate radio frequencies for communications purposes, run airports, design reservation-making systems, must have their efforts constitute a coordinated program.

Numerous other examples exist of the need to conceive of and design a potentially useful combination as an integrated system, and so to avoid the alternative, which offers not just less efficiency, but complete unacceptability. A very mundane example shows the principle, although not worthy of the efforts of a systems approach team. Suppose we have in our home a heater, a cooler (air conditioner), a network of ducts, a thermostat to sense the temperature, and a control system that will turn on either the heater or cooler as the temperature reaches the low or the high settings on the thermostat. Let us imagine that we have connected these items together without considering the interaction effects. We want a 70-degree average temperature.

Let's start the system by closing the circuit when the temperature in the room is, say, 68 degrees. The thermostat, having been set for 70 degrees, will ask the

THE SYSTEMS APPROACH OR CHAOS

heater to come on. It responds and works up a load of hot air to send into the house. When this heat pours in, the thermostat will reach 70 and quickly go to 71 and beyond. At this point, the thermostat asks the heater to shut off and calls for the cooler to come on. This the cooler does obligingly, but as it gets underway it has to push the warm air out and get the cold air in. The warm air temporarily keeps coming into the room for a while and the thermometer moves on up to 73 or 74. Seeing this, the thermostat demands that the cooler work even harder. So now really frigid air is being prepared. When it finally gets into the room it brings the thermostat back past 70 and, with the momentum of the cold air coming along in the ducts, on down below 70 to 69, 68, and 67. The thermostat, registering what has happened, now frantically asks the cooler to go off and the heater to come on prepared for an all-out effort. Meanwhile, the temperature falls to 65 and below. This time, the control system is quite alarmed by the drop in temperature. It asks the heater to do much more than it was called upon to do before. Moreover, now the heater must push that additional cold air out through the system before the warm air can really be felt, so the thermostat keeps dropping for a while.

The oscillation builds up until the absolute capacities of the heater and cooler are reached. We will have our 70 degrees, on the average, but by a steady repeated oscillation between 55 and 85 that goes on all day and night. We have all the components to keep our room near 70 degrees, rain or shine outside. And we attain a

THE SYSTEMS APPROACH OR CHAOS

70 degree average. But we have managed, by inadequate consideration of how the whole system works when everything is connected together, to create a situation that is absolutely unacceptable. It is so unsatisfactory, in fact, that it is more than worthless, a liability. Its performance is outside the category where we are concerned with cost and efficiency. We don't want this air conditioning system at any price.

Imagine an automobile highway built between two main population centers, with other important points in between, its capacity set during the design as a tradeoff of economics against performance. Present and future traffic flow and adjacent land utilization were basic considerations, we assume, in the design choices. Suppose, however, that carelessness concerning interrelated factors existed when the system decisions were made. Specifically, in setting the entrance and exit locations along the highway it was not anticipated that a sports stadium would be built. Assume, as luck would have it, what with the highway project taking several years for construction, the unplanned-for stadium was opened soon after the highway was completed. Result: on sports days, an important highway off-ramp is saturated. This causes a backup on the highway along that "fourth" lane, leading to that lane's being lost to through traffic. But it is worse than the lanes' diminishing in number from four to three. Little preparation can be expected by the driver approaching on that lane from a distance. This causes a series of sudden, extemporized lane changes by drivers from lane

THE SYSTEMS APPROACH OR CHAOS

four to lane three that dislocates lane three's use also, an effect that backs up. In fact, it so expands to the remaining two lanes that movement on the entire highway comes to a complete standstill.

Now something as significant as the coming of a sports stadium would not often go unnoticed. We are suggesting, however, that it is becoming increasingly tough to arrange to take proper account of the numerous factors and the way in which these will interact and change with time. Unincluded developments and growth of volume or intensification of a characteristic or two may not be merely a handicap to a system; they could result in frequent complete stoppage of operation. We have all read about the situation some time ago where on an approach to a bridge in one of our large cities the traffic remained at a standstill for so long that hundreds of drivers, in despair, disgust or panic abandoned their cars and left the scene. The mess was not straightened out for days.

Unfortunately, one example we can cite of threatened complete disintegration, resulting from inadequate consideration and handling of the major parameters of what is a systems problem, is the typical large city. Housing, mass transportation, automobile traffic, social issues, education, removal of wastes, air pollution, water supply, electric-power reliability, distribution of food and matériel, crime, medical care—the list is overwhelming. The rate at which the problems are getting out of hand is greater than the rate at which they are being solved.

THE SYSTEMS APPROACH OR CHAOS

Cities do not constitute good systems designs. They never were system-designed. Redesign, where possible, to make cities into better overall systems is hardly taking place. The socio-economic factors are all out of balance. The sources of revenue move away from the city as life and work within it become less acceptable. Take any urban problem, and we are likely close to that threshold of intolerability in many communities where the whole system will fall apart. A city nearing that threshold will commence to be abandoned.

Over the coming decades, as hundreds of millions are added to the population of the world, new cities may be built and existing ones extended. Those designed or redesigned by the systems approach with proper consideration of all the factors will be superior, both socially and economically. They will offer better living, higher income, and greater social stability. They will be laid out so that the flow of people and things, the arrangement and provision of services and access, the educational, medical, and recreational facilities will all compose well with each other and with the work and life pattern of the people who live there.

CHAPTER V

System Design, a Necessary Step to Component Availability

THE systems approach is becoming vital for still another reason. Without a good systems analysis and system design as a first step, or at least as a parallel effort, it is not easy to understand and specify the necessary pieces of the solution. If the parts required are not called out, no one will set out to make them available. These components, which the systems design will bring together into a harmonious ensemble to meet the problem, include many items: needed equipment and matériel; people trained in specific jobs with spelled-out functions and procedures; the right kind of information, stored and flowing, so that the people and the things know what to do and where to be to make the whole system operate.

Let us look at some examples of the need for systems work to tell us what components we need. Take improved educational systems. We know that we must greatly enhance educational resources and techniques to provide for more and better education for more young people, for retraining of adults for new jobs, and for expansion of the abilities of most of us to keep pace with the requirements of the society. We particularly need a massive rise in educational potency in poverty areas.

SYSTEM DESIGN, A NECESSARY STEP

Now, to meet these needs, we have reason to believe that technological aids can be very important to extend the effort of the human educator much as X-rays and electrocardiographs and blood tests assist the physician. These aids include special films, closed circuit TV, electronic language laboratories, computer-based education and training programs, and other equipment for the presenting of educational material, the handling of data and information, and for assisting the educator and administrator in planning, analysis of results, and research. But what specific technological devices will accomplish exactly what within what educational framework? If computer-based teaching machines are to be installed, how are they to be used so as to yield real advantages instead of perhaps the disadvantage of creating a sort of robot teacher or evolving to a simple source of entertainment? To answer, we must consider such things as the psychology and principles of teaching, the choice of what is to be taught, and how the results will be measured. The actual hardware and software design of some new teaching devices may be the easiest part of the system engineering, once we really see what we need.

Now it is possible to conceive of technological aids coming into the educational system on a very gradual basis, with the systems approach quite secondary, or in the background. Individual ideas such as, let us say, a series of films for classroom use on a particular subject, might be produced by some entrepreneur and sold to the schools at a profit. Here and there inventors are pro-

SYSTEM DESIGN, A NECESSARY STEP

posing computer teaching programs or electronic gadgets that might be attractive to some educators as an adjunct to the existing educational process. But unless the devices and the films are used very broadly, the prices would probably be too high for the aids to make much of an impact. A few school districts might innovate; the government might provide some grants to university groups that will try out some ideas at a nearby primary school; some educators, in isolation from the technologists, might dream of some things they would like to have. But if no integration takes place the whole can not move forward.

Systems considerations are, by these approaches, far off in the back row. To see this more sharply, let us imagine a school of the future as it might be if technology is used to the fullest by a good systems approach. It doesn't matter whether the description about to be given is totally accurate. The fundamental point of the need for a systems approach becomes apparent if anything like the kind of educational system to be described is even considered—even if such consideration is only a step in getting something else and better for the future than the authors would presume to be able to picture now.

Imagine a lecture room in which the students are seated at computerized desks. Each desk's console has some means for identifying the individual student, such as logging on the system with an identification code. The logging-on starts a record of that student's participation in that particular classroom hour. The lecture presented

SYSTEM DESIGN, A NECESSARY STEP

is a well-arranged video with accompanying examination material. It describes a principle, re-describes it another way, and gives examples. Then, periodically during the presentation, the filmed instructor pauses to ask reasonable questions, the answers to which involve the student at each chair entering responses. Thus, as the lecture proceeds, the record builds up in the computer, the electronic filing system in the basement of the school, of how well each student is responding to the lecture.

This central computer will do something else. It will have stored in it, for that particular lecture, an expected "par" rating for the student's exam responses as the lecture proceeds. If the students are especially bright that day, and if the computer observes that they are scoring consistently higher than "par", then the computer will call for the program to be speeded up, skipping some of the repeated explanations and examples. Conversely, if the students appear not to be getting the right answers often enough, the program will be slowed down automatically, with the insertion of additional prepared explanations.

So some of the day in the school of the next century might be spent in this kind of a classroom. There are many other possibilities. Another part of the day might involve a student alone in front of an individual presentation machine learning trigonometry by watching the explanation before him on the video screen. If he is an especially able student, his answers would so reflect; each trigonometry presentation, and hence the whole

SYSTEM DESIGN, A NECESSARY STEP

course, could go very rapidly for him. For a poorer than average student the presentation would again slow down automatically.

We see that electronic technology here could do more than simply substitute for a presentation by a teacher. It could also participate in examining the student's understanding. Moreover, the system could adjust itself to the apparent ability of the student to learn. Finally and equally important, technology could make it possible to keep a record of the student's progress as he learns. Electronic technology applied to this kind of information handling, as a component of a new educational system, could also process the data on the accomplishments of the students. It could compare the total overall progress of the pupils in a course based on a particular prepared presentation with alternative presentations. The human educator trying to understand a student or a course plan would now be aided by pertinent data.

Now if anything like this one example—and we can cite many others of potential radical changes in educational techniques—is caused to happen, then look behind the scene. We can hardly bring off so major a change without research on how one learns and how we should use these technological devices to aid education. We need to try out experimental devices, and we need to create programs. We must bring together many experts: in the subjects to be taught; on how to teach and present material, how to analyze results, how to plan; in statistics; on young people; on the curriculum; on the technology of the devices; on the economics; and even

SYSTEM DESIGN, A NECESSARY STEP

on certain political factors involved here. Somehow, all these talents and experiences must be assembled into a team arrangement.

With rare exceptions, good systems engineering will have to be accomplished before really useful educational technology will advance to the point where practical devices and programs will be conceived, produced, distributed, and paid for. It is not likely that private industry will produce useful, efficient, economical apparatus—and the right kind of computer-based teaching programs—unless there has been enough systems work to lay the foundation for a large market. This market can exist only after the machines and the programs of learning with which they are to be concerned are thought out on a sufficiently broad scale. The teachers, the education researchers, the technologists, and the citizens who must vote the funds must see how the entire operation relates to desired results, how it compares with alternatives for the effort expended. They will want to know how these technological systems will affect the student and the student/teacher relationship. The systems work has to break this "chicken before the egg before the chicken" chain.

The systems approach is also a necessary initial or parallel phase to assure the proper roles for the human elements of the system—teachers, operators of equipment, maintenance crews, originators of the programs, authors of the text material. All these individual functions cannot be worked out offhandedly or overnight. If they are attacked in a random, piecemeal

SYSTEM DESIGN, A NECESSARY STEP

fashion, then compatible roles will take a long, long time to develop. If the tentative systems designs can be analyzed in depth to see if they represent good solutions to problems or needs, it will greatly accelerate the availability of the system, because it will make clear what precisely are the required pieces and what are the significant roles for all system elements, be they humans or machines or computer networks.

Consider another example of the way in which the systems approach is a virtually necessary step if needed components are to be envisaged and made available. In that imagined large hospital we viewed earlier, there is always the problem of providing the test data on patients to the physician in a timely, reliable, and economical fashion. An integrated computer subsystem may be the best solution to acquisition, storage, dissemination, and display of test information. It would probably include computer terminals available for interrogation by the physicians at convenient locations, perhaps even in each patient's room or as portable devices. The physician would enter some code into the computer, a process no more complicated than using a telephone, to identify himself and his patient. He could then select the desired information from a supplied list of alternatives. The system would then immediately respond by displaying the called-for information.

Similar electronic display devices are currently in wide use, of course. Stockbrokers can query their computers to find out the last sale price of any listed stock. Up to date to within moments, and covering the whole world's

SYSTEM DESIGN, A NECESSARY STEP

stock exchanges, this information system makes stock-brokers more knowledgeable and productive. Similarly, a clerk at the airline reservation counter today can hear your request to travel between stated points at particular times, push some buttons, and see readily whether a seat is available. So we know, technologically, that such information systems and devices can readily be designed to provide instant medical information for hospitals as well.

But precisely what kind of computer system is right for the hospital information service? What must be its capacity? What resolution must it be prepared to display? In what way must it be designed so as to be a good fit with the physician's brains, fingers, and eyes and so as to be capable of handling the specific kind of data required? What information will the physician need to collect or retrieve, in what form should the information be displayed, and how should it tie in, that is, communicate with, the rest of the system—the data base, laboratories, X-ray departments—that causes the information to be collected and stored?

The answers to where, what, and how cannot come solely from a designer working somewhere in some computer hardware company. Nor does it make sense for some entrepreneur or inventor of such component devices to ask physicians what they would like to have and how much they are willing to pay for it, so as to decide whether to develop a component for the hospital market. It cannot happen this way because no one can ensure that the imagined component will fit into an

SYSTEM DESIGN, A NECESSARY STEP

information network in a sensible way as a working, practical member of the whole system until the system is designed. You cannot gamble that you will sell your product into a system should it finally evolve. It would be like your writing the oboe part for the second movement of an orchestral suite that someone else may or may not compose. That is no way to run a symphony.

Another example of a systems project where the systems approach has to lead, or progress in parallel, before we can get the components is one the U.S. government has sometimes undertaken. It is to analyze the problem of moving people about as required by their work, residence, and perhaps just their inclinations, in the most highly populated section of the United States. This is the Northeast Corridor, oftentimes called the "BOSNYWASH" megalopolis, almost a solid urban stretch from Boston to New York to Washington. Here it is readily predictable that, unless superior ways are found to provide transportation for people and things, frequent interruptions, severe bottlenecks, limiting social constraints, and a net drag on the nation's economic growth and general well-being will result.

When we read about urban or interurban mass transportation on the ground, half of our attention goes to futuristic vehicles described as operating at sensationally high speeds. But we are not likely to have new trains, new engines to drive them, new tracks built, new computer controls developed, new rights of way created, new feeder roads and ticket booths and bond issues and required legislation—not unless the whole

SYSTEM DESIGN, A NECESSARY STEP

program has been worked out in sufficient depth and competency so that the interrelationship of all factors becomes clear and sensible to a substantial majority of voters.

The potential manufacturers of apparatus for this high-speed system will not see a clear market for the sale of their apparatus unless there has been a good and accepted systems design study. Such an approach must consider not only the patterns of how people live and work and transport themselves to do both, but how these are likely to change in the future. One cannot consider a public ground transportation in isolation. Included must be the way it ties into air transportation and personal automobile transportation. The cost and effectiveness of various combinations of ground, air and automobile transportation, and even waterways must be estimated, as must be the effect on the total environment.

What good is it to be able to move rapidly between two adjacent cities by high-speed rail transportation if the system hasn't been designed with enough completeness to allow for getting from your home to the rail station in a sensible way? If a personal automobile must be used to do that, then there had better be a way to get the car parked when you get to the station. Another point: it will be necessary to route the high-speed ground transportation through some areas not so highly populated today. This will enhance the population buildup there and minimize, as a result, what might be more costly modifications that would have to be made to existing cities if they were to handle the anticipated increased

SYSTEM DESIGN, A NECESSARY STEP

population. But such a route is not as good, perhaps, for those now living in existing cities. What is the tradeoff, the relationship or give-and-take between benefits and penalties here?

There are an infinite number of solutions, not one best solution to the problem. Even the job of setting up criteria that are useful to compare one solution with another is a tough systems job. The transportation system serves the people that live in the area; but the people will live in the area to some extent because of the existence of the transportation system. Without investigating these broad systems questions, without looking at the interactions of some of these basic parameters, how can one hope to judge intelligently the speed and capacity of the system and its cost? Or how to enhance any aspect of performance? Or what should be the physical descriptions of all the needed devices, controls, communications, and the facilities, terminals, ticketing—and the whole works?

To be sure, you have to begin somewhere. It is understandable that individual industrial organizations who hope to participate in producing equipment for the BOSNYWASH complex would seek to start early, to speculate on the kind of things that might be expected of them if they are to be successful contributors. But before they commence the actual development and building of embryo equipment, the unifying, integrative effect of a systems approach is mandatory.

CHAPTER VI

The Tools and Talents of the Systems Team

UP until now in this book we have concentrated on providing a feel for what the systems approach is about and why it might be considered as an important integrating technology to bring science and engineering more fully into the solution of the problems of our society. It is time now for us to take a somewhat deeper cut into the details of what it is that experts in the systems approach actually do when they go to work on a problem in the real world. In delving into this next level of intricacy, our goal certainly is not to make a systems engineer of the reader. Perhaps a fair way, though somewhat oversimplified, to describe the objective of this chapter is to explain why systems work is not likely to be done well by amateurs.

In describing the nature of the systems approach, we made much of the fact that in using this tool we look at a problem with completeness and think of it as a multi-parameter problem, as it indeed is. Looking at problems this way, with the purpose of obtaining sensible solutions, we seek to be logical and objective, to consider all of the interactions among the various parts of the problems. We noted that we give attention, from the very beginning, to setting down the goals with clarity and using the goals to create criteria for evaluation of alternative approaches.

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

All of this, we emphasize again, sounds like just ordinary common sense. Any of us who are intelligent, accustomed to thinking straight, a bit innovative, perhaps, as well as sound, and who get in and study our problem deeply to learn all about it, will presumably organize our effort. We will not go off in all directions at once. When we arrive at the solution, we will know it is the best practical one because we will have considered all alternatives of merit, that again being ordinary common sense. Also, we will expect to look into as many details as we can. Some little and trivial part will get only a little of our time. We will try to figure out and concentrate on the dominant factors, the ones that appear to matter if we are going to come up with a good solution rather than some Grade B or Grade C result.

What, then, distinguishes us, with our natural, intelligent approach, from the professional systems engineer, the team of "techno-political-econo-socio-experts" who will approach the problem in a "professional" way?

Most problems worth talking about have so many facets, with such puzzling and complex interactions, that to analyze them requires individuals who are highly trained, who have great experience, and who by the practical selection process of success or failure emerge as especially gifted in the kind of analysis and design involved. In addition, these people have created a set of special tools. We shall try to describe some of these by way of examples. Behind these tools are many abstract concepts and specialized mathematics. Also required is

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

knowledge of people, physical phenomena, and apparatus that none of us is likely to understand well without considerable studying and working in the field. Of course, the systems team must include people with minds of exceptional breadth of interest that transcends any one specialty.

Is there really such a thing as a professional in understanding people, by whatever name—psychologist, psychiatrist, humanist, historian, sociologist, or anthropologist? In the context of this text only a limited answer is proper. We are speaking here only of experts in understanding people as members of an interconnected group of people, machines, matériel, and information flow, with specific well-described and often measurable performance requirements. We all know about how complicated people are and how little we truly understand about them in general. It is nevertheless possible for systems engineers to become wise about people as systems components. This results from the unique experience systems engineers get in designing and studying the workings of systems with people as members.

From the beginning, the human components must be specified and evaluated as to cost, performance, stability, and time for development and training. Hopefully, this is done just as adequately as we list the specifications for the inanimate portions of the system and subject them to analysis. It goes without saying that we are on weaker ground here, of course, less confident that we can extrapolate the behavior of people, as we do with

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

machines and equipment based on the laws of physical science. But the experience that we have had with human beings is not useless, by any means. In some situations, for example, we can unhesitatingly reject a proposed systems design because we know it asks too much of the human beings in the system. By contrast, in other situations we may find it more difficult to accept or reject a system on the basis of doubts about some simple electronic component, such as a semi-conductor chip. Sometimes it is evident that a man can and should perform a function for which a mechanical device would be far less appropriate.

We have had long experience with the extension of and substitution for man's muscles by machine. Here, it is a matter of good engineering to select those functions that can be better performed by a machine: the application of large forces, operation at high speeds, movements of precise magnitudes, operations in dangerous environments, and the like. Ideally, we do not have a man dig a ditch; we have him steer a machine that does the digging. Man is capable of subtle motions and the application of complex combinations of forces tied in with his senses. He should be reserved for such situations.

Something similar is indicated in the extension and replacement of man's senses and his brain. No computer in existence has an intellectual capability transcending more than a fraction of the intellectual tasks a human brain can accomplish. It would be wrong, then, to consider replacing man by a completely automatic

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

system in all situations in which he uses his brain or his senses. But again, a human's remarkable system is being misused if given easy assignments to do—too easy for the tremendous powers of the brain and sensing system—or if the speed of operations and memory capacity is beyond handling by humans, or the task is tedious and tiring to an extreme.

To illustrate, consider a constant decision-making operation in which there is at the most a need for deciding between two or three possibilities easily identified (such as separating objects by their color as they pass by at the rate of thousands per second). This is simultaneously a job too simple for the human system and yet, in sheer quantity of simple actions per unit of time, well beyond human speed. The degree to which the system is to be made automatic, the specialized education and training required for the human operators, and the extent to which the human eyes, ears, and brains will be used as participants in the systems are all considerations that play a major part in modern systems engineering. This kind of systems engineering cannot be done unless the team is equipped with knowledge, experience, and tools of the trade that have to do with assessing and comparing the abilities, investment in, maintenance of, and reliability of humans versus machines or computers.

We have emphasized the need for the systems-engineering team to have competence in the handling of interdisciplinary problems that cross all the specialties, technical and non-technical. We must add a point of

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

emphasis concerning two completely technological aspects of the team's total talent requirements. One of the frequent characteristics of modern systems engineering is setting out to do things that represent radical advances over past accomplishments. In the process, we have to make use of the very latest in scientific knowledge, sometimes using new scientific discoveries before the fundamentals are well understood by the scientists dealing with these phenomena. This alone would require that the team include scientists intimately acquainted with the frontier fields of scientific research and who arrive at that acquaintanceship because they have been engaged successfully in this kind of exploratory work.

Another aspect also involves the research scientist. When you try to understand the workings of a very complex engineering system in a quantitative sense, then the thought processes are not very different from the attempts good research scientists make to understand any complex segment of nature. They try to write the laws of behavior of the system. They devise experiments, sometimes of a unique nature, that will test their hypotheses. The minds of individuals capable of analyzing and predicting the actions of a complex, multiparameter man-made system are much the same as those who are capable of improving our understanding of the basic laws of nature.

But while it is true that modern systems engineering rests on a broad scientific foundation, it is also true that it is equally dependent upon known engineering techniques and upon existing components and subsystems.

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

The "practical" engineer is needed not only because he has the necessary store of information on these subjects, but also because he has the practical touch to make the system work as planned. This is especially important in systems containing large numbers of components with complex interconnections. We even need the kind of practical fellow who is good at "debugging"; we don't want to have to call in an Einstein every time something doesn't work (and probably he would disappoint us if we did). There are some people who have a knack for pulling out of the symptoms a diagnosis pinpointing the difficulty and then can go on to straighten things out.

A systems engineer is quite accustomed to getting a question in reply to his question. For the design of a large medical center as earlier discussed, the systems engineer asks, among hundreds of other preliminary questions, to see the scope of the problem: how many patients will you expect to be handling, how long will they stay, what kinds of things will you be doing for those patients? He is bound to be told that these numbers can only be guessed at and that any definite answer can be justifiably questioned. Available are some facts about what happened in the last several years and some estimates or speculation by the physicians and the health authorities as to what might happen in the future. Evident also are some biases in those who are trying to decide what the role of the medical center should be in the community and in some opinions concerning the community's health situation, improvements in future control of disease, and future changes in longevity.

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

Changing governmental and private health insurance plans may greatly affect the potential requirements at the center. Meanwhile, the population is growing and shifting, and other hospitals are going in and out of the area or changing their capacities and approaches. The answer as to what the hospital should plan to do in quantitative terms depends on the answers as to what it will cost to do it, and these answers won't be known until a system design is completed and can be subjected to good costing analyses.

So the systems engineer is faced initially, even in trying to state what the problem is and what the objective is, with the same inevitable "which came first, the chicken or the egg" problem. The "facts" of the matter are not simple, clear, absolutely determinable quantities. They are statistical in nature and they can only be described by stating a range of possibilities. Beds per year, X-rays required, heart patients expected—these are all only expressible as probabilities associated with the possibilities, ranging from an indefinite minimum to an indeterminate maximum.

How do you design for situations in which the basic parameters and the data describing the performance requirements to be met constitute a whole spectrum of possibilities? At the very least, you must be prepared to carry through in your analyses a spread of these possibilities, not just one. But, more especially, you must have systems engineers who can deal with quantities when they are statistical and indefinite in nature. First of all, it takes someone trained in statistics to collect the

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

pertinent data and list the possibilities as to their relative probability. People skilled in thinking precisely about imprecise quantities are needed.

Most of us know enough probability theory to be able to say that if you flip a good coin, there is one chance in two that it will come up heads. A few who have taken some courses in probability mathematics can figure out from this that the chances of getting two heads in succession are one in four. Some of us who have had the course very recently might even be able to figure out what the odds are of getting three heads followed by four tails. But it takes someone quite expert in statistical analysis and probability theory to figure problems like the following: If, on the average, you have 100 heart patients needing a private room, how often should you expect to have 150 patients requiring attention and how often only 50, since the 100 average figure is merely an average, and absolute steadiness in the coming and going of heart patients is not to be expected? If you provide 100 beds, how often would you probably have to turn away patients and how often would you have beds unused?

Another good question to ask has to do with expected growth. The community to be served by the hospital is expected, say, to increase gradually from the present population to a doubled population in thirty years. During that time the average age of the population is expected to increase. If there are no changes in the tendency of people to report to hospitals for treatment, and recognizing that the old come more often than the

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

young, what will happen to the number of beds required? How is this changed if, recognizing fluctuations as part of the statistical character of patient flow to the hospital, we wish to cut down the number of times we must turn away patients for lack of a bed by 25 percent, or by 50 percent?

The statistical-probabilistic nature of all the facts with which the systems analyst and designer must deal is not confined, we see, merely to the conditions and data surrounding the problem. Probability applies equally well in stating what the goal for the system should be. Imagine that in designing an internet computer system we are trying to decide what the requirements on the design should be as to the length of time it takes to reach the internet address entered. If the capability desired for the system is such that within one second after placing the request the network responds, then there will be many channels not contributing to the working network but waiting for a good deal of the time for requests. On the other hand, it is intolerable if most of the time the customer has to wait ten minutes before the connection is made. How do we state what it is we want? We must state it in statistical terms. For instance, we may specify that 90 percent of the time we must reach the desired internet address within 15 seconds. Of course, this implies that, in putting down such a condition, we understand how much longer than 15 seconds the time delay will be the other 10 percent of the time.

Neither the facts underlying any problem, nor a statement of what performance we would like the system

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

to possess, can be stated in anything but statistical-probabilistic terminology. Behind the terminology are difficult concepts to handle which requires sophisticated mathematical tools and understandings.

But there is more. The sub-system elements of the system are themselves unspecifiable in definite, absolute terms. A couple of gears, for example, cannot be called to have, as to their relative positions as they mesh with one another, absolute precision. Always a certain amount of slippage and free play between the gears is inevitable. If one gear is positioned, the other one will occupy a band of positions within that amount of free play. Similarly, in typical systems, information must be communicated, stored, handled, and transmitted by people or computers to other pieces of equipment or to people. There is always "noise on the signal," static on a radio channel or a telephone channel. There is never absolute fidelity of transmission of information. If something is written down, it may be written down incorrectly. People make errors and fail to enunciate clearly. Computers are misinterpreted or mis-programmed.

Now, of course, as to all components of a system, whether people or equipment, pieces of paper with information on them, or communication channels, we may strive for a very high precision. We can even design the system with elements of it that are included with the function to check and confirm. We can add expense and complication, and, oftentimes, delay in the speed of operation, all in the interest of trying to get closer to

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

absolute definiteness in measuring precisely how every part of the system will work and in controlling that part to work as planned. But we can never make them perfect, never guarantee against the ultimate failure of a component.

In some system elements, it is practical to approach near perfection and to remove all significant indefiniteness in performance. For example, generally speaking, we design bridges with tremendous safety factors. Concrete portions may have imperfections, and so may tiny portions of steel from which the bridge is built. However, to compensate for such un-removable shortcomings, everything about the structure is designed for super-redundancy so that one weak element, even if it is there, is paralleled by many other strong ones. We choose to have no more than, say, one chance in a million that the bridge will collapse in a hundred years. We choose the elements of the bridge, monitor their quality, and compose them in such a manner that even though an individual part can fail because it is not perfect, the combination's probability of failure, that of the bridge, will meet our requirement.

In other instances it is entirely acceptable for the system to fail occasionally. Thus, it is acceptable to enter the wrong internet code, so long as it doesn't happen too often. It is very annoying if your letter is delivered by the Post Office to the person next door, by mistake, but usually not catastrophic. It is an important part of systems design and analysis to understand well the relationship between the odds that imperfections and

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

impairments will occur and the consequences and cost, respectively, of their occurring or their being prevented from occurring. The systems approach, properly applied, will disclose the degree of sensitivity of system performance to the quality of the system's elements.

There are other times when it is not completely a matter of our choice to be able to hold down to an unimportant level the possibilities of failure or delay in a system. Thus, we really may not know how to design a system intended to isolate high level nuclear waste from the accessible environment for 10,000 years (the standard imposed by the U.S. government). If, despite this, we produce such a system anyway, we must have reasons for believing it to be worth it to do so, to make the investment, even though the protection afforded may not be complete.

So the basic facts of a system are statistical; the performance characteristics desired for the system have to be stated in probabilistic terms; the individual components of the system operate with and can only be described with some indefiniteness. Let us now add that there has to be always a statistical characteristic to most of the analysis and design that make up the work of the systems engineer as he goes about envisioning systems and trying to understand how they will operate in relationship to the problem. Let us look at examples of these analyses.

Every system usually involves analyses of queuing—the "waiting-in-line" problem. For instance, how many elevators do we need in a building? This depends, of

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

course, on how long we are willing to wait for the elevator. If we know this fact, we still must analyze the probabilities of people jamming up, all wanting the elevator at the same time, at many floors. The systems engineer might start with some averages for the number of times people have to move from one place to another in the building. This requires careful analysis of the functions the people are carrying out, the timing of carrying them out, and the change of locations required to do so. If a thousand people are going to leave the first floor every hour on the average by elevator, and if each elevator will hold ten people and change floors in 15 seconds, how many elevators are needed so that 70, or 80, or 90 percent of the time—you name it—people will queue up for the elevator no longer than two minutes, or three minutes, or whatever you wish to specify?

In a highway design, given some experimental results concerning fluctuations of speeds of individual cars as they move along together at 65 miles an hour, how close can they be to one another before massive interference effects set in that cause starts and stops of jammed-up traffic? If a lane can hold cars 50 feet apart, traveling at 65 miles an hour, thus enabling a calculated number to pass a point on that lane per unit time, what happens to that flow as that pattern catches up with a pattern ahead of cars that are more closely packed, traveling less fast? If a lane has to pour out into an exit which permits only one car per minute to pass through a stop sign, how long a line of cars will queue up in front of the exit if somewhere, way back, the cars are arriving as stated at

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

65 miles an hour, 50 feet apart? What will be the rate at which that traffic jam will be reflected back along the highway? At what point, how many miles back, will the traffic have to slow down from the original speed of 65 miles an hour?

Similarly, imagine that in a modern hospital we are designing, an automated, computerized communication network has been included to provide “nearly instantaneous” test results to the physician when he identifies himself and his patient by entering some information on a computer. Unless we are reckless with our money or determine by analysis that it pays off to be deliberately luxurious in communication channel capacity, we might find during the operation of the hospital's communication system that several physicians are trying to interrogate a computerized data source at virtually the same time. Considering the speed of electronics, the physician may not know that he is number three in line when such a jam -up occurs because the information may come to him, even as the third man, within a few seconds. But we have to be able to make the calculation that tells us that it is a few seconds, and not many minutes.

Accordingly, to deal with the numbers that describe real-life goals, desired performance, functional descriptions of system equipment and human components, and, indeed, to understand the basic patterns of operation of a system, the systems-engineering team must be expert in statistics and probability mathematics. It must also be

THE TOOLS AND TALENTS OF THE SYSTEMS TEAM

continually logical, consistent, and clear though living with natural, pervasive, and persistent indefiniteness.

CHAPTER VII

Cost Effectiveness and Tradeoffs

THE previous chapter was a quick introduction to the tools and talents of the systems team, including the important statistical and probabilistic aspects of systems engineering. The discussion went only far enough to show that there is a lot of technical sophistication in the thinking required, in the mathematical tools used, and in just the practical handling of the myriad of necessary basic data, performance, and component characteristics inherent in a system. We sought to suggest that to be expert in the handling of such problems one requires much training and experience.

Now, in this chapter, we assume that we have this ability to handle voluminous, puzzling, and statistical data. We also assume that we have been able to separate the wheat from the chaff and that where we do not have the information we need, we know how to go about getting it, or estimating it. If we are forced to the wall for lack of data, we assume the necessary information will be built up on the basis of a combination of some theory and some past experience.

We next want to add a bit of solid substance into what we have been meaning all along about being "quantitative." We want to explain why it is necessary in achieving good systems analysis and design to be able to measure the quantities determining the competitive

COST EFFECTIVENESS AND TRADEOFFS

approaches. Since we shall have to compromise, getting something at the expense of something else—like cost versus time, or speed versus reliability—then we are also interested in understanding the concept of "tradeoffs." We shall want to see how we can relate measures of goals to the cost of attaining them. It can be put the other way: We want to know the resulting costs and other penalties of poor performance, or of failure to provide sufficient capacity, or speed, or to account for some rare, but perhaps significant, possibilities. We shall proceed by example.

For a medical center design, let us ponder the matter of how much in the way of drugs we should keep readily available. This is an inventory problem; it is faced by every business, industry, and government operation and even in stocking our pantries at home. A hospital has its own cost-effectiveness and tradeoff aspects, because its value measurements are different from most other operations. New approaches to medical care emphasize a more cost-effective approach to providing medical services. Some things must be stocked even if they are unlikely to be used for a long time and rather expensive to store, because the penalty for not having them is too high—for instance, the loss of a life. This is one penalty that cannot be completely stated in dollars; others can.

Let us suppose we are speaking of a rare serum that must be refrigerated and otherwise closely controlled, rather than stored in a casual way. Moreover, it must be checked on and replaced, because it tends to spoil. Our investment in this serum is, as a result, very high. At the

COST EFFECTIVENESS AND TRADEOFFS

same time, if we don't have it in storage, it is not necessarily true that we will lose a patient as a result. We may be able to get the serum from elsewhere in sufficient time. Maybe that requires chartering an airplane in an emergency, but that special expense could easily be costed against the expense of keeping this item in the inventory. Of course, we would have to be reasonably confident that the other source of supply that we plan to tap won't fail us. Again, no one is ever sure of anything, so we put down the probability of having good serum in our refrigerator, versus the probability of being able to get it outside, considering reliability of the source, its own inventory problem, and the reliability of plane travel on short notice. Here are alternatives that we rate according to reliability, probability, cost, and time delay, pitting these ratings against criteria of hospital performance.

This serum inventory item is an extreme. But it illustrates the point that good systems engineering involves getting into a tremendous amount of detail and putting quantitative measures on everything—very often, cost and time measures. Let us mention other inventory problems. We can carry large quantities, thus buying the supplies cheaper, or small quantities that we pay a higher price for. Interest expense on the money invested has to be compared with the price drop, against the amount of space used, and against spoilage. Here again, sharing with other sources nearby has to be considered and costed, and time and reliability measures have to be put on each alternative.

COST EFFECTIVENESS AND TRADEOFFS

In any inventory system where things go in and out at all times, there is a real problem in knowing what you have, in placing orders to resupply early enough so you do not run out and yet do not have an overly generous supply on hand. So you must set up to account for everything, to observe the reduction in supply as items are used up, to place orders at the right time to the right place. Some sensible plan for the amount of various items to be carried is necessary for the efficient renewing of orders. Inventory systems can become very complex and costly in themselves. But their cost of installation and operation can be examined against the money to be saved, because a good inventory-control system keeps the inventory investment down.

Let us go to another example. As will be a little clearer later when we discuss information flow in a complex system more thoroughly, the cost of a sophisticated, fast, convenient electronic medical test-result information system in a hospital must be measured against the value of the improved service to be rendered. Here, to set value criteria requires that we ask ourselves what counts most. We have to put priorities and weights on numerous conflicting demands. Is it really worthwhile to put in a costly information system that can handle more information and do it more reliably and more rapidly? Does greater availability and accuracy of information create savings elsewhere in the system? Does it provide (rather difficult to measure) improvement in the quality of health care?

COST EFFECTIVENESS AND TRADEOFFS

For instance, the higher -cost electronic information system may save the time of physicians and nurses. To measure this means you have to be willing to assign a value to the doctors' time in walking about a large hospital to go to a central place to get information; the time of nurses and others in putting the results of tests down on paper so the doctor can see it later, the reentering of those pieces of information on more permanent records, the filing and reassembling of those for later perusal; and the calling on the telephone to get other human beings in the system to go look at files. All of these things cost money. In principle, every one of these pieces of time can be estimated. Always some of the items you must list in envisaging improved system approaches can be cost-estimated, if only approximately, even though other things may present great difficulty in being reduced to quantitative considerations.

If the analysis shows that almost every approach is tied for first place, then you might suspect that the winner in your cost estimating may have been sort of arbitrarily decided as a result of your rather equally arbitrary estimating of some factors you cannot presume to know very well. The systems engineer will decide to track down those numbers and get to know them better because they are important in the decisions of design. Or he may decide that it doesn't make too much difference, because the alternate approaches, when studied carefully, look equally satisfactory. Or, that for this system configuration, the performance is rather insensitive to large variations of the parameters. At least, the

COST EFFECTIVENESS AND TRADEOFFS

system designer can perceive those situations where there are great cost differentials that he would never otherwise have known about had he not been forced to a quantitative evaluation of as many of these parameters as it was reasonable to pursue.

An example of a difficult cost-estimating problem is to figure the likely numbers of mistakes when relying completely on human efforts as compared with the number of mistakes likely to result when computers are used for most of the handling of most of the information. If you are unable to state some reasonably reliable averages for the number of mistakes made by people and machines, and various combinations of both working as teams, then you will not have a very good basis for comparing the relative values of automating or not automating—because, in a hospital, mistakes in the handling of medical test information can be very important. To obtain evaluations here the systems engineer may find it desirable to put some people and computers together in various patterns and run a few experiments.

Let us take another example, far from hospital design. Consider a system designed to isolate highly radioactive nuclear waste by-products from nuclear power plants from the natural environment. This system could cost several billion dollars for the development, operation and maintenance over many years. Let us ask how a systems engineer would go about putting some cost-effectiveness values together in order to see if such a system can be said to pay off. Suppose that for this

COST EFFECTIVENESS AND TRADEOFFS

sum of money we can expect to collect the nuclear waste generated by nuclear power plants across the United States, transport it to a central location, store it in engineered canisters and place it in a tunnel thousands of feet underground. A centralized storage location would provide for positive control and long-term monitoring. With no such system, the still radioactive spent nuclear fuel stands in pools at each of the power plants near urban areas scattered across the country. As the power plants are retired and no longer produce power, the infrastructure must be maintained to ensure containment of the radioactivity from the waste. If the objective is to ensure control over the nuclear power plant by-products, then a central repository with engineered barriers may provide the surest solution. On the other hand, the cost of removing the waste from its current storage at the power plant will likely be high and the environmental consequences of an accident occurring during transport, while the probability can be made low, would be grave. Cost-effectiveness analyses must take into account not just the cost of maintaining the nuclear safety and security issues long- and short-term.

As a final example, let us try to understand the value of a public higher educational system. Some of the problem lends itself to quantitative analysis. We can put down some figures for the cost of education in various categories, such as law, medicine, engineering, business, and teaching. We can then examine the statistical data on the incomes of individuals in these categories as compared with the incomes of non-college-trained

COST EFFECTIVENESS AND TRADEOFFS

individuals. We can compare this difference in lifetime income with the investment in the education. We can look at the tax structure as it is and as it might be and estimate the fraction of this added income that returns to the state and that is thus available to continue the educational system for the next generation. Such quantitative cost studies are far from a complete evaluation of higher education. But they should be useful to the voters and decision makers.

In a similar way we could consider major changes in the educational system in urban areas heavily populated by low-income groups. Again, we can do a tradeoff analysis on the cost and effectiveness of major steps to broaden the scope of the educational system in those areas against what might be the increased value to the society of educating this group to a higher income potential. Here, we are speaking of dollar-and-cents evaluations. There are obviously other, qualitative, values as well. To put everything you can think of down and try to be quantitative about it all is foolish. It is equally foolish, however, to assume that nothing can be said with numbers about complicated human problems, that we can get no guidance from analytical examinations of some of the factors. This kind of negative thinking results in our citizenry being taxed to educate people poorly—so poorly, considering their environment and diminished opportunities, that they are unable to contribute adequately to the productivity of the society as a whole, unable, in effect, even to support themselves. They are often on relief rolls which are

COST EFFECTIVENESS AND TRADEOFFS

funded by taxing the productive citizens. Some improved system might readily be shown to have at least the potential of taking added initial cost and converting it over a period of years to a much greater output than the original investment.

No matter how complex the situation, good systems engineering involves putting value measurements on the important parameters of desired goals and performance, of critical pertinent data, and of the specifications of the people and the equipment and other components of the system. It is not easy to do this and so, very often, we are inclined to assume that it is not possible to do it to advantage. But skilled systems engineers can change evaluations and comparisons of alternative approaches from purely speculative to highly meaningful. If some critical aspect is not known, the systems experts seek to make it known. They go dig up the facts. If doing so is very tough, such as setting down the public's degree of acceptance among various candidate solutions, then perhaps the public can be polled. If that is not practical for the specific issue, then at least an attempt can be made to judge the impact of being wrong in assuming the public preference. Everything that is clear is used with clarity; what is not clear is used with clarity as to the estimates and assumptions made, with the possible negative consequences of the assumptions weighed and integrated. We do not have to work entirely in the dark, now that we have professional systems analysis.

CHAPTER VIII

Optimization, Mathematical Modeling, and the Computer

THERE is a classic academic problem in calculus that involves a glass of wine and a heavy spherical ball. We imagine the wineglass to be full, and we carefully lower the spherical ball into the glass, displacing some of the wine. Now, if we choose a very tiny sphere, it will displace an amount of wine just equal to its own tiny volume. If we now choose and immerse gradually larger spheres, we shall, with each increase in sphere diameter, keep displacing more wine, again equal to the size of the sphere. But when we try spheres so large that they will not go fully into the wineglass, then, as we keep increasing the size of the sphere, we soon arrive at a point where very little wine is displaced because the sphere's surface is so flat, so slight in curvature, that it protrudes hardly at all down into the wine.

Now, somewhere between the tiniest sphere that displaces very little, and the very large sphere that also lets almost all of the wine stay contently in the glass, there is an "optimum" size of sphere, the one that displaces the maximum of liquid. The calculus exercise is to express the size of that optimum sphere in terms of the dimensions of the cone that makes up the interior of the wineglass. This is a problem that is readily solvable by writing down a few mathematical equations, provided

OPTIMIZATION AND MATHEMATICAL MODELING

one fully understands and is experienced in the procedures of differential calculus. It is useful to us for some points in this chapter—though displacing wine is not exactly what a systems engineer usually has to consider in a problem of hospital design, transportation system analysis, or in applying the systems approach to the optimizing of the use of natural resources. One of the things it tells us is that when you can express relationships by mathematical equations, then you can go further with advanced mathematics to pinpoint the maxima and minima for the various variable parameters as they are related to the given or fixed ones.

Another thing we can learn from this example is made clear if we consider an ordinary cylindrical water glass. Here you see we have no problem if we ask what size cylinder to insert into the glass to displace the most liquid. Try to put in a cylinder that's larger than the glass and it won't go in at all and will displace no liquid. Put a cylinder of smaller diameter in, and you haven't done as good a job as you might in displacing fluid. Clearly, all you need is a cylinder that just fills up the volume, is just under, in diameter, that of the glass, and is also equal in height, because beyond that it does you no good either. Our point, then, is that in some instances, the optimum (the maximum, or minimum, as the case may be), is obvious; we need no higher mathematics to see it. But real-life problems are much more complex. It usually takes a lot of mathematics to figure out the optimum relationships to handle situations where one must study the variations of each parameter as others are altered and

OPTIMIZATION AND MATHEMATICAL MODELING

use the results of the study as a guide in the systems design.

Let us illustrate this by some examples closer to practical life. Suppose you are designing a rapid-transit rail system for a city. Among the large number of questions you must keep asking and answering as you start to tie down the most intelligent systems design is this one: If you put the stations too far apart, then the people who use the system have to take a long time from where they live to get to the station, the average person being somewhere between two of the terminals. If you put one on every block, the typical passenger needs to walk only five minutes to a station. However, by the same token, you have apparently fixed it so that the train must come to a halt at each block. So now it takes very little time to get to the station, but it takes a long time for the train ride. Given the average distance of the users of the system from the actual track line and some mathematical formulas that the systems engineer can synthesize to describe the time spent by the train en route as a function of the number of station stops and the time spent by the passenger in getting to the station, we can then set up a mathematical relationship for the overall time that the typical passenger will spend getting to and from his destination points. Then, by the use of mathematical techniques again, we can "optimize" this and find the best spacing of stations for the minimum of time to be spent by most passengers.

Of course, this particular optimization problem is but a segment of overall systems design. There will be many,

OPTIMIZATION AND MATHEMATICAL MODELING

many such subproblems: cost, as related to the number of stations to be built, the speed of the trains as related to the number of starts and stops, which impacts back on cost; rights of way; the fact that the population density will not be uniform along the run of the line. All of these things add to complexity, but do not change the general idea.

Here is another example. We have 1000 acres of land to be divided up for residential use. It is mostly flat, and we can choose to have a large number of small lots or a smaller number of large lots. The smaller lots will deliver us more in the way of selling price per square foot. From this standpoint, subject to some bottom figures that we cannot go below for a salable lot that meets the city's restrictions, it would be best for us to cut up the property into as many small lots as possible. However, we must also put in streets. The more lots we have, the more streets we are going to have, since every lot needs access. Land going to streets will lose us gross income. So there is an optimum size of lot and corresponding street plan. What is the largest number of lots into which we should divide up this property? This should not be guessed at. It needs to be figured carefully, especially since the real problem involves many other constraints, some hilly parts to the land, some areas with views and others without.

Here again, we have considered only a part of the problem. But a good systems engineer will set up a large number of these questions and get the answers to these pieces as a step in guiding him to the elimination of a

OPTIMIZATION AND MATHEMATICAL MODELING

good many poor approaches. Equally important, it will enable him to observe some optimal figures, which other considerations may require be deviated from, but which can serve as a target or reference point along the way toward putting the entire solution together most sensibly.

Another example is the selection of the location of a new road to be built. An agricultural area centered at A serves two population centers, B and C, which already have a very good multiple-lane highway between them. The plan is for us to put a road from A to the B-C highway in such a way as to minimize the number of miles that the trucks will have to travel to carry their produce to market. If A were equally distant from B and C, and if B and C were equal in terms of their market size, the problem would be easy. We would just draw the road from A as a perpendicular into the main highway. But these situations do not apply. It turns out that C is closer than B, and B has a substantially bigger market. We can diagonal the road from A over to either city, cutting down the time it takes to get to that city, at the expense of increased time to the other. Where should the road connect to the highway, as a function of the relative distances, the relative size of markets, so that the total operating expense to continue to serve both markets profitably by use of a single road will be minimum? Again, given the facts and figures, a systems engineer can use calculus to get pertinent parts of the answer. The decision-maker can then more easily weigh and integrate the other nonmathematical facets to arrive at a superior decision.

OPTIMIZATION AND MATHEMATICAL MODELING

The typical systems problem has not only many overlapping optima to consider, as we have already said, but any one problem usually has a multiplicity of fixed and variable parameters. When we write an equation for a time or a cost or a distance that we wish to maximize or minimize as a function of many other given conditions, it ends up being a very long mathematical equation indeed in the typical practical situation. But this is not all. Some of the conditions that we mentioned as being fixed are themselves busy interacting on each other. When we were considering how far apart to space stations on the transit system earlier, we implied that the population would stay fixed at some specified densities along the route. Actually, we have to recognize a severe system problem: depending upon where the stations are located, the population will shift. Some people will tend to move where transportation is easiest. Apartment buildings to accommodate them will rise near the stations. Others will move away from the transportation facilities because of noise and congestion.

Similarly, when we build a new road from the fruit and vegetable center that favors one of the two cities as a principal market over the other by cutting transportation costs to one, then it pays the producer to lower prices a little bit in that one city and try to unload his vegetables there. There is competition for sale of the producer's output against canned goods. Thus, a change in price structure of fresh produce, which itself depends on the cost of trucking, comes back around to alter the pricing in the market. Moreover, there are, presumably,

OPTIMIZATION AND MATHEMATICAL MODELING

competitive, though poor, roads that can be used and will be used more or less depending upon where the new good road is placed. These are examples of unknown, less quantitative factors that must be integrated using judgment rather than advanced calculus or computers. That integration will be easier if the known, quantitative parts are handled well.

Some of the conditions that we might like to have fixed, so that we can optimize others when we understand the relationship, must be dealt with not as single fixed quantities but considered instead merely to be restricted to an estimated range. As we indicated earlier concerning the probabilistic and statistical effects of all of our data, this is an inevitable condition. As a design technique, the systems engineer has to go around the circle many times, considering a range of values for a while for most factors, gradually tying down which factors are most important in setting conditions and influencing performance or cost, or time, or any of the many resulting characteristics that he seeks in the solution.

Certain facets of practical problems are not numerical but rather, shall we say, logical. That is, sometimes the condition is that if we do one thing, we cannot do the other. We have an "either/or" condition to consider. For example, in an interurban -transportation-system design, we can give a customer of the system a category such as pedestrian from home to station, or as a driver of a car to the station with a parking problem, not both. Some of the relationships the systems engineer sets down are on a

OPTIMIZATION AND MATHEMATICAL MODELING

yes or no basis, rather than expressed in some sort of quantified formula.

The net effect of all of this optimizing is that it usually cannot readily be done by head and hand. The systems engineer may be able to set up the formulas, but he has too many things to keep track of, even aided by the highest mathematics. His problem is not very different in principle from what we have if we try to multiply two huge numbers with a hundred digits each. In principle, we can do it. We would need too long a sheet of paper, however, and too much time; and we would be very unlikely to get the right answer because of the tedium of carrying through all of the steps in the longhand multiplication that we most certainly learned to how to do in primary school. The process would represent no basic mystery to us. We would be prevented from being an adequate problem solver, not because of lack of understanding of the basic theory, but rather by the sheer quantity of the steps involved. We would need a computer.

Just as you and I need it for long-division or multiplication when the numbers get to be big enough, so a first-class systems engineer needs it for the large number of quantified relationships he has to deal with, even when he understands the mathematics, in principle, very well and has been quite capable of setting up all of the relationships.

The computer simply goes through all of the tedious steps that make up the typical analytical solving of a problem. Of course, there are other problems where the

OPTIMIZATION AND MATHEMATICAL MODELING

mathematics becomes so complex that no mathematician knows a way to solve it in a formula sense, the way we know how to add or multiply, or take square roots. Under these circumstances, the computer is an enormously able tool. It can be engaged in a kind, of trial-and-error process. We program it to approximate values for the numerous factors, use relationships among them we postulate, and, by a series of steps (sometimes millions or more) predict the performance of the combination.

Such repetitive trial-and-error approaches are, in principle, possible for a human being, of course, without the computer. However, the difference in speed between the computer and the human being in handling such detailed steps is a factor of a trillion or so. A new computer performs the once-inconceivable trillion mathematical operations per second, a measure known as a teraflop. The machine is so fast and has so much memory that it can simulate complex events—like explosions, nuclear fusion reactions, missile impacts or the crash of a comet into the Earth—with a fineness of detail that was impossible before.

Unaided, a human cannot keep track of, store, and access volumes of information. So fast is the modern electronic computer, so skillful has the systems engineer become in programming it, and so large is its capacity to keep track of a large number of quantities at once and bring them into play as required, that the computer can be used to simulate the operation of very complex systems. What we mean by this can be illustrated by an

OPTIMIZATION AND MATHEMATICAL MODELING

example. Let us suppose we are designing a highway system with many entrances and exits and we have laid out a tentative systems design. We now would like to know how well it might work. We need a "model." So we construct a "mathematical model." We ask the computer to imagine that the cars feed in and off the highway, going through a typical day of peak hours and off hours. We tell the computer about the traffic we expect, the statistical variations away from the peaks and the averages that we have assumed in our first design. We tell the computer what we guess about the frequency of use of various entrances and exits. Around the statistical averages we have assumed we tell the computer to inject appropriate random deviations. We include some settings of traffic signal patterns on the streets around the highway entrances and exits since they can have a great effect on the entrance and exit conditions. We program in our theories about how the drivers will position themselves on the highway and the relationship between speed and closeness with which one car follows another, variations in speed chosen by individual drivers, and the mathematics describing the way in which those variations will "travel" in a wave down a crowded lane to build up and cause jams.

A computer, properly programmed with all these relationships and statistical facts, assumptions, theories, equations, and conditions injected, will then tackle for us the predicted operation of the highway. The computer is now boss of the "mathematical model" of the system. The computer will arrive at flow patterns along all the

OPTIMIZATION AND MATHEMATICAL MODELING

lanes of the highway, showing the speeds as they change with time, the traffic at all points, the number of times that lanes come to halts, ins and outs at entrances and exits—in short, the performance and capacity of, and the time required to travel on the highway to get from one place to another.

Having examined this simulated highway operation, the systems engineer now can alter some of the programs, seeking better performance and more realistic and accurate predictions of performance. In this way, the systems engineer can approach what looks like the most sensible overall design. The same can be done with the computer model to predict cost and time to build the highway. This can be done for any aspect of the design.

All in all, next to the human brain of the expert, the computer is the most powerful tool of the systems approach. By itself, it has been enough to make a major difference in the usefulness of the systems approach to a broad range of problems of our society. The teaming up of the skilled systems engineer, a good mathematical model of the system, and the computer to "work" the model constitute a powerful force for valuable prediction of operation of systems—especially when the systems are much too big, complex, long in building, costly, and vital to be left to trial-and-error revision or to gambling as to the performance of the system after it has been brought into being.

To a systems expert, the simulation or modeling of a system is straightforward when dealing with the "quantifiable" aspects. When relationships can be

OPTIMIZATION AND MATHEMATICAL MODELING

expressed in mathematical terms and the basic data that define the principal elements are available, then, in principle, the systems engineer can simulate the workings of any system. In practice, the modern computer enables him to operate the model and thus observe the simulated system performance even when the number and complexity of the relationships and the quantity of data to be handled are all high. But the typical system has nonquantifiable, in fact, unknown, parameters. How does modeling and simulation work then?

We can relate for example, overall performance characteristics of a central repository system for nuclear waste to costs and to the characteristics and limitations of leaving the waste in place at nuclear power plants. But which of the alternative scenarios will provide the greatest protection to the public at the lowest risk of contamination? Similarly, we can model on a computer the entire quantifiable operations of a new rapid -transit system for a city, but will people elect to use it, to what extent, and when?

We can still benefit from modeling and simulation, despite such difficulties. First, we can set in all the measurable and known aspects. Second, we are still privileged to use all the intuition, judgment, and decision-making available to us to introduce all the possibilities or assumptions we think ought to be considered for the nonquantifiable aspects. Third, we can then see how the modeled part of the system responds to each of our assumptions, adding our own

OPTIMIZATION AND MATHEMATICAL MODELING

selection of weights to be given to the relative importance of the various possibilities we selected for the unknown parameters. Thus we will have made our judgment a part of the model.

The simulation exercise will tell the decision -maker about the performance of the rapid -transit system, but not whether people will like it and use it. On the other hand, if that decision -maker will introduce his guesses of the degree of public acceptance, the model can relate it to cost to the user and performance.

CHAPTER IX

Function and Flow of Information, People, and Matériel

HAVING established some appreciation of what we mean by the systems engineer's being quantitative and of how the systems approach brings value measures and competitive analysis into play, let us backtrack a bit. Before we can be quantitative about the details when we attack a complex systems problem, we must first visualize the configuration of the main components of the system and how they mesh together. We must block out what the key aspects of the system are to be—people, equipment, interconnection between them, and so on—in order to get the job accomplished. As we design, we may alter this framework and composition of the system many times. We are unable to evaluate any part, set any performance attribute, or estimate any costs, until we begin to see the configuration of the ensemble of components.

Toward these ends, the systems engineer begins very early to plot the flows that make the system a harmonious and compatible group of connected elements that has a chance of performing the task for which it is intended.

Thus, for an electric -power generation and distribution system, the systems engineer will show in diagrammatic

FUNCTION AND FLOW

form how the energy flows as it is converted from the basic fuels to steam in boilers, then into steam turbines; or from waterfalls to water turbines to electric generators; then through transformers, through switching systems, transmission lines, and out to the various users where, again, it is altered in form many times. This would be an energy flow chart, and it would serve as a backbone around which additional systems considerations will be studied. To accompany this an information flow chart would be created because none of the switching systems, motors, generators, and people, acting over what might be a very great geographical span, would know what to do unless they are directed to do so by a control network that moves the information about, stores that information where required, processes it, interprets it, etc.

In an air-transportation system there are obviously many flow diagrams that are essential: flow of the vehicles, passengers, airline personnel, reservation making information, accounting information, scheduling information, matériel, spare parts, even of luggage. All these separate flow charts have to integrate with each other, and each one has to show how the various basic parameters—information, personnel motion, vehicle movement—relate to one another.

If we were called in to examine the system used to track and manage an offender through the operation of a criminal justice system (arrest, booking, court appearances, detention) with a view toward improving it by installing computers wherever sensible, we would put

FUNCTION AND FLOW

down a description of how all of the people and information move about in this justice system. We would show how decisions and control tie in at various steps of the flow process. We would then try to see what is most fundamental about all of these flows to find which must be regarded as rigid and determining, as we install computers.

To examine the flow of medical-test information in a hospital, we would show such data originating at the source, or maybe even before that, in the mind of the physician who calls for the test to be made. We would note how this order connects to the patient and to the hospital's information-control system and to the medical-test personnel and facilities such as the X-ray and the blood-test technicians. The flow diagram would be completed only after we have disclosed how the information gets back to the physician who wanted the result, how it is stored, and how it is utilized to make the next step happen according to some sensible plan.

Equipped with the basic flow structure, at least as a tentative first step, the systems engineer would next show professional skepticism and curiosity, desire for logical, quantitative completeness, for surrounding the entire problem and considering alternatives objectively.

Why all this information? Who wants it, when, with what accuracy, where, and in what form? How available must it be, where and how must it be stored, and for how long, and who said so? Is it just a habit, a pattern of experience that comes from some earlier way of operating the hospital that might have been good for its

FUNCTION AND FLOW

time but is not now sensible? Who are all of the people involved who have access to the information or who participate in acquiring it and transferring it from one place to another? What are the interactions on this medical-test information? Does it go to accounting, to charge the patient for the test? Does it go to some statistical file for analysis of hospital operations with a view toward planning ahead for improved facilities to make future tests in a superior fashion?

If these answers are not known, or if they seem to be provided arbitrarily or somewhat mysteriously, the systems engineer insists upon getting it tracked down. Where the answers are not known or inadequately accurate, the systems engineer tries to acquire them.

Throughout all of this analysis the information flow diagram may change many times, with many tentative and novel schemes being considered. Then, cost evaluations, cost effectiveness, quantitative criteria for judging, optimization, tradeoffs—all the concepts behind these words are put into play.

This is a convenient point for us now to bring in personnel flow and personnel function charting. When we look at the information flow, we will question what various people are doing in the act of collecting or recording or moving information along. Must they do this? Is this the best function? Do we have nurses and doctors doing things with information that are clerical in nature and could be done better or at least more cheaply by other personnel? Is the flow of personnel determined by the fact that our information system fails to provide

FUNCTION AND FLOW

the information where it is needed, so people are moving about at a great rate using up their time in the corridors and imposing conditions on the physical layout of all the hospital facilities to cater to such a less-than-optimum information system?

But what applies to information handling, as regards its interaction on what people do and where they are and how they must therefore move and use their time, applies to every other aspect of what goes on in the hospital. We must therefore chart in detail, with all interconnections taken account of, what all people in the act are doing. Then, we must be equally skeptical, curious, complete, logical, and objective in considering the modifying of those functions.

The motion of matériel, of course, is tied in with the information that controls it and to people and equipment that use the matériel, whether it be blood plasma or drugs, X-ray film, or paper forms to be filled out. And obviously all these flows and functions—for information, matériel, and people, their physical arrangements and layouts, the timing, quantities, accuracies required, and reliabilities interconnect with each other. Which is another way of saying that the systems engineer has no choice but to study all of his flow patterns over and over again, continually revising so that there is consistency among them. And as systems engineers do this, they continue to try to make quantitative all the basic descriptions of what they have before them, so that they can make cost effectiveness and optimization studies.

FUNCTION AND FLOW

Because all of these flow patterns tend to become very complex, with multiple routes and interconnections for all of the basic parameters shown in the diagrams, the systems engineers need computers for keeping track of these numbers and interconnections.

CHAPTER X

Feedback, Instability, and Nonlinearity

IN this chapter we shall show that a system may in some respects be quite a sensible one, performing as called for in the flow charts, and yet be capable of operating in a completely different and undesirable mode. It may become "unstable." It may do what is intended—and some very, very peculiar things as well that are quite unintended and often surprising. The system may respond well within a particular environment, when subjected to particular, shall we say, average conditions. Then it may display quite erratic or, at any rate, unsatisfactory behavior when the conditions are somewhat different from average. This must be anticipated by the professional. Analysis for these fractious conditions is as important as for the expected and typical conditions.

Let us cite some examples. It won't do for the designers of a telephone system to overlook the possibility that someone may leave the phone off the hook. This is not the way the system is supposed to work to accomplish its primary mission of communication, but it has to be expected that the system will be called upon to react to such a condition upon occasion and it must not go completely berserk when so stressed.

FEEDBACK, INSTABILITY AND NONLINEARITY

Remember a few chapters ago, when seeking an air conditioning system, we connected a cooler, heater, thermostat, some controls, ducts for the air to flow in, and some rooms, and hoped for an arrangement that would keep the temperature fairly close to 70 degrees at all times. Suppose it had been deliberately our intention to arrange instead that the room temperature should oscillate between 55 and 85 degrees, swinging regularly from one to the other, averaging 70 but never coming to rest at it. For either objective—the 70-degree temperature held constant, or the average of 70 degrees with constant hunting and swinging of 15 degrees to each side—notice that we would still need the same components mentioned above. We would require for both the sources of warm air and cold air, the ducts, the thermostat, the control system to turn the units on and off, and, of course, the rooms for the air to go in and out of. In the earlier example, we indicated a possibility that we will get the fluctuations whether we like them or not, that they might be wild, and that the whole system might be highly unsatisfactory. On the other hand, we know (all of us, from experience) that engineers can design a system that keeps the temperature reasonably constant. With proper design, when the temperature gets a little higher, a little cold air is introduced. When the room turns a bit colder, some warm air is introduced. So, whether we keep the room close to 70 degrees or sustain the big oscillations, all has to do with the details of design, the way in which the interconnections are made, the time delays in response to observed changes, the

FEEDBACK, INSTABILITY AND NONLINEARITY

capacities. All of these parameters must be brought into some appropriate relationships.

This room air-conditioning system is too simple a problem to fully illustrate the powers of the systems approach. However, it is an example of "feedback," a term that indicates not only that the components are connected one to the other, but that there is a feeding of something important in the output back to the input of the system. Feedback is generally present throughout systems whose connections among the components consist of many closed loops in which some phenomenon or characteristic or ingredient of the system is passed on from one component to another, is affected by it, and the same ingredient or measured quantity or parameter comes back around to the starting point. Let us make this clearer by sticking to our example.

Our flow ingredient is temperature of the air in the room. It is observed by the thermometer on the thermostat, and this observation is interpreted by a series of steps that eventually result in air being brought into the room from the heating or cooling unit. The air flowing is now again sampled by the thermostat. The air's condition is the result of changes caused by the measurements on the air's condition. Its condition thus "feeds back" to affect its condition.

It is when such a feedback situation occurs that it is possible, in principle, to have oscillation, runaway effects, and, in general, instability. If the system isn't properly designed, in other words, the thermostat could ask for "hot," but by the time the output air comes back

FEEDBACK, INSTABILITY AND NONLINEARITY

to that same input point, the thermostat finds it is now too hot and asks for "cold." If the loop has the wrong kind of flow rates, time delays, and capacities, then the "cold" that it has asked for will be observed later as too cold and there will be a request for hot again. The reactions may build up to a permanent oscillation, rather than calm down to some steady point from which only small deviations occur.

An inexperienced driver of an automobile, a beginner, starting out with the teacher at his side, pulling away from the curb and beginning to move gingerly down the street, can run into this instability problem. He over-steers. His eyes are the measuring instruments. They tell him that he is drifting over to the right. He calls upon his arms to turn the steering wheel to the left. As the car responds, he becomes overly concerned because eyes tell him that the car is shifting much too fast, now, to the left, so he steers fiercely to the right. Thus he commences an oscillatory pattern that gets out of hand.

Perhaps trying to ride a bicycle—if you don't know how— suggests the idea even better. Or trying to move at some reasonable speed backwards in an automobile, out of a driveway, looking out the rear-view mirror and adjusting your wheel from right to left, to try to keep from hitting the two curbs. It's not easy, is it, to do this? You tend to get bigger and bigger adjustments until you have to stop, pull forward, and try again.

In simple situations, it is possible to get along without feedback. For example, if we want to keep a house at a

FEEDBACK, INSTABILITY AND NONLINEARITY

reasonable temperature, we have the choice of eliminating the thermostat and control system entirely. We note the temperature in the house in the morning; then, on the basis of our expectancy for the day at that time of year, set the furnace to operate to produce enough heat to make up for that we expect to lose because of the cold temperature outside. For instance, we can set the furnace for "medium" and set it to run for three or four hours. It may get too warm in the house, or may not be warm enough, but that is a chance we take. We might wish to come back in a couple of hours, make an observation and an adjustment. We have now created a loop and put ourselves in it. In this sense it is a feedback system, but during the time that we were unavailable, it was not. The system had no chance of going into wild oscillations, instability, hunting, and runaway. In a similar fashion, on a hot day, we could shut down the furnace, turn on the cooler to some setting, go away and leave it, confident that while we might miss our estimate, no instability, no hunting, will set in.

But in complex systems of the kind we have been discussing in this book, where there are many, many interconnected components, and where what happens at one point is influenced by what happens at other points, where we bring the information around the loop purposely to make this influence felt, and, indeed, where we have to do that or we have no system worth talking about, then feedback is always present. Where it is present, we must allow for the fact that there will be

FEEDBACK, INSTABILITY AND NONLINEARITY

unwanted transient effects and, perhaps, even steady effects, with the system oscillating around the basic performance that we intend for it. If the oscillations constitute small deviations, they may be quite tolerable, in effect the same as slight inaccuracies. Then we have no need to be perturbed. But we must be certain this is the case. Similarly, there may be times when there will be large unacceptable reactions of the system, but we have been able to build in a defensive response to this large reaction, one that causes it to die down very quickly so that the disturbance is momentary, even though it would have been significant if it had been allowed to remain.

An example: The quality of factory production on a certain product is assured by checking out the performance of the completely assembled product. The separate parts that make up the assembly are checked only by a sampling process in the normal operation of the production line. More specifically, only one part in a hundred is checked carefully. The systems configuration, however, provides for an automatic switch to another mode of operation. If in assembly the product fails to pass the performance test, then not only is it rejected, to guard against shipping bad products, but automatically the procedure changes. Now all parts are checked carefully, each one being gone over and bad parts rejected so they will not reach the assembly.

Now, this sounds all right, especially if we add that the supervisors are alerted whenever the change of mode just mentioned takes place. They get in and try to find

FEEDBACK, INSTABILITY AND NONLINEARITY

out why the parts quality is running below the required level for the product to work well after assembly. However, if the system is not properly designed in detail, within the concepts just described, then we can have an unstable hunting and oscillation. Thus, when the parts are all checked out and bad ones rejected, then only good ones reach the assembly line. The assemblies will run perfectly again, since there is no longer any reason they shouldn't, when performance of the complete product is checked. At this point, the system will revert automatically to the earlier mode, in which only samples of the parts are checked. In that mode, however, bad parts will begin to come through again. Then the assembled products will show failures again, which will automatically call for a change of mode back to checking out and rejecting parts again.

In a simple "loop" such as this one for quality control, we can readily surmise that it should be fairly simple to so set the rules and operations of the system as to avoid this kind of useless oscillation. The possibility lurks, however, because the output of the system is measured and caused to affect the input, which in itself affects the output, etc. The circle or loop of feedback that may provide instability and hunting is there. In complex systems involving many, many such circles and loops, it is easy to appreciate that it might be difficult to pick out and understand and prevent all of the unsatisfactory oscillations—at least, it is difficult if we are not expert at the handling of feedback and stability problems.

FEEDBACK, INSTABILITY AND NONLINEARITY

Earlier in the text, we suggested the possibility of technological systems in education that would permit video presentations to be made to a classroom of students who would periodically respond to questions put to them as the presentation progresses. We indicated that the program would consist, not of a single video, but actually of a series of short videos. A presentation of a principle would be followed by a near duplicate of that presentation with some novel touches to make it more readily understandable by repetition and variety, and followed then by a number of examples, and some questions. We then suggested that, depending upon the accuracy of students' responses by entering responses into computer terminals at their desks, responses that would be noted by a control system, the presentation could be speeded up or slowed down.

Here, you see, we have a feedback system. A central rating or "par" for that presentation would have been set initially. If the students seem to be registering unusually well, that is, way above par, in their response to the questions, then the next presentation would be speeded up with only one way of looking at the principle presented and only one example perhaps, rather than several. The speed of the presentation, while set initially at a "par" value, would be subject to change. As the presentation is speeded, however, observations on the "output" would continue to be made. Questions would be thrown at the students during the presentation. If the accuracy of their answers should now fall off badly, then the presentation would be slowed.

FEEDBACK, INSTABILITY AND NONLINEARITY

We can thus imagine that a typical class presentation would involve the system's continually speeding up, slowing down, speeding up, slowing down. If this is not excessive, that is, if it is within the range that we have thought about and planned, so much the better. The students would not be aware of what was left out. They would go along listening, watching, and replying. They would, on the average, be receiving a presentation that is at a rate set by their apparent ability to understand it—just what we want. Some variation of the speed of presentation back and forth would be considered necessary in a good system. Failure to use the feedback idea would vitiate the whole new concept, namely, automatic adjustment of the teaching speed to the student's apparent ability to learn.

On the other hand, if the system is not properly designed, then the oscillations could be large, and very unsatisfactory. The presentation might speed up too much, leaving all of the students with little understanding of the material presented. This would be followed by the observation that the students appear to be stupid, as they start missing answers. The system might then overshoot to an exceedingly low presentation rate, much too disrespectful of the ability of this particular group. It could hardly be worthwhile to have a presentation and examination system that is usually either much too slow or much too fast and nearly right only for an imperceptible moment.

Now, the setting of the proper relationships obviously requires very sophisticated, professional, qualified

FEEDBACK, INSTABILITY AND NONLINEARITY

competence in systems design. It is partly mathematical, partly experience, partly common sense, partly detailed specialized knowledge; partly the setting up of the right kinds of scientific experiments. It is not easy, and not for amateurs.

So much for stability and "unwanted" modes resulting from feedback. The design of systems is made more difficult and requires unusual technical knowledge because of still another phenomenon. "Nonlinearity" is difficult to handle and generally always present in real-life problems. Nonlinearity refers to the fact that there is not a straight-line relationship between the important parameters. We meet this in a simple way every day. The old adage that two can live as cheaply as one may not be true, but it is true that two together do not require necessarily twice the cost for one. If so, it would be a nice, simple "linear," straightline relationship. Again, if it costs 40,000 dollars to build a 1000-square-foot house, it does not necessarily cost 80,000 dollars to build a house twice that large. What it does cost depends on a lot of other things besides. There is a nonlinear relationship between cost and square footage.

Remember the old problem we had in primary school: If a chicken and a half lays an egg and a half in a day and a half how many chickens do you have to have to lay a dozen eggs in a week? Well, the way we got the answer to that was to assume "linearity"; fractional chickens behaved in a directly proportionate way to a full chicken—half a chicken would lay a half an egg in

FEEDBACK, INSTABILITY AND NONLINEARITY

the same time that a full chicken would lay a full egg, or take twice as long to a full—that sort of thing.

In systems problems, we have, of course, to handle nonlinear phenomena, many times over, with so many interlocking complications that unless we are skilled in higher mathematics and in the use of the computer, we can hardly make these necessary, and oftentimes elementary-appearing, calculations. Let us take a few simplified examples.

We ask how many cars can move at 30 miles an hour, spaced 100 feet apart, on a single highway lane past a given point, and we work out the answer. Next, we double the speed of all the cars, keeping the spacing the same. If we could really guarantee this same spacing as equally safe and executable by the drivers, then twice as many cars per minute would pass that point on that highway on that lane. But, obviously, as the speed increases, the idea of keeping the same spacing begins to be questionable. At some speed region, above a low one that we might start with, a whole set of nonlinear phenomena will begin to set in. A slight variation in speeds of individual cars, as a result of their drivers' performances, or the cars', and each driver's performance in response to what he sees ahead of him or thinks he sees, will all have effects on drivers behind, as we have had occasion to suggest in another context before. Waves or ripples of acceleration and deceleration tend to build up and bunch up, so that we not only change the safety situation greatly, but we simply cannot hold to the straightline linear ratio. Twice the speed, in the sense of

FEEDBACK, INSTABILITY AND NONLINEARITY

an allowable or attainable speed by the individual cars, does not mean twice the number of cars passing down that highway per minute. As we alter speeds, the traffic refuses to "scale." Instead, it becomes a different animal entirely.

People are notoriously nonlinear. Suppose we have one man making some observations and registering what he observes. Then, let us assign a second man to independently repeat the act. In this way we hope that if the first man makes only one error in a hundred—an intolerable result, let us say—the other man is unlikely to make the same error on the same individual action. If his rate is also one in a hundred, the two together would cause us to have a wrong answer only when they err together, one time in ten thousand. Let us say this is a tolerable accuracy. But we have to watch whether one of these people has an influence on the other, and whether his accuracy is preserved as we vary the rate of observations. If we have too few observations per hour to make, the man may get bored. If we try to speed him up, say, to double his rate, his errors may rise, not to two in the two hundred we've now put in place of the original hundred, but maybe to ten or twenty in two hundred.

If all key variations of real-life phenomena were linear, there would be more good systems engineers, because it would be easier to be one.

CHAPTER XI

The Impact of New Technological Components

ONE reason for the present growing importance of the systems approach to many "social engineering" problems is that the solution of these problems includes a significant advanced technology ingredient. We are speaking here not of the use of technological tools used by the systems engineer to get the systems analysis and design accomplished. We mean, rather, that if you have a problem that is very complex in almost any field of endeavor, at this time in the history of man you generally find that some combination of men and machines is the best way to do it, rather than man alone. This is so, whether your task is building a highway, designing a stock-exchange information system, an insurance company's data bank, a police department's command and control system—you name it. Moreover, in recent years, a particularly pertinent area of technology, electronics, has expanded in its capabilities, versatility, flexibility, and the economical availability of its hardware. We are able, through this area of technology alone, to provide command, control, communications, interconnection for action at a distance, and to remember and handle colossal amounts of information at once and still keep everything straight. As a result, systems that a decade or two ago would have been

THE IMPACT OF NEW TECHNOLOGICAL COMPONENTS

completely out of the question, today can be envisaged, built, and made to operate satisfactorily.

Not only has the art of systems engineering been greatly transformed by advances in technology, but technological components have revolutionized the system. With new systems art we are creating new systems products.

Present jet travel, in terms of the distance and number of passengers transported, and the scheduling required to handle the passengers, would be quite impossible if the airlines could not provide a virtually instantaneous reservation-making ability nationwide for nearly any flight that you request. The system works only because with today's electronics applied to reservation-making systems, you can get the answers to whether or not a reservation is available on a specific flight between two cities, on a specific day, essentially in no time at all. Systems keep track of the passenger's name, seat assignment, food desired, and a few other things as well. It is not that the system would be somewhat slower if everything had to be done by hand, by direct human-to-human communication and the paper -and-pencil setting down and looking up of figures. It just wouldn't work at all. Without advances in the electronics of telephonic communication, the long -distance calls alone that are necessary to airline reservation-making would be uneconomical and slow in operation. Without computers the information could not be acquired, stored, processed, and interrogated. The passenger requests would

THE IMPACT OF NEW TECHNOLOGICAL COMPONENTS

continually saturate the system so that nothing would get through.

In a modern city, when considering ways to create a sensible traffic management system so as to get the largest number of people through the streets in the minimum of time with the greatest safety, one has to consider the synchronizing of traffic lights by means of a computer and sensing devices that will observe the traffic and communicate the observations to the computer.

A modern police department has to ask itself whether it should not revise its procedure for assignment of the available officers in cars so as to get the greatest of coverage and crime prevention per man on the force or per unit of cost. Such revisions require not only two-way communication, but that the cars' positions be known to a computer system that can display the instantaneous changes of location and can, as a matter of fact, originate signals to the cars automatically. Careful analysis beforehand would show how to program the computer so that when some cars move in response to conditions as they develop, other cars will be caused to move to optimum new locations trying to provide at any given time what appears, on a statistical basis, to be the best spread of locations. If this is done well, it would be the equivalent of adding to the total intelligence directing the patrolling of the area. It might give the effect of many more officers and automobiles at a lower cost. Whether it does or does not may not be obvious. More so is the fact that good systems engineering is required if

THE IMPACT OF NEW TECHNOLOGICAL COMPONENTS

the police department's leadership wants to be in a position to judge the impact of all this new technology on how a police department might now be best operated.

The availability of the computer as a component has caused a revolution in the way many systems should be put together. When we speak of a system as a complex of man and machines and a flow of information and matériel that connects them all together, the machine component is quite often a computer or other electronic device. A process-control system for a large oil refinery is now a new kind of man/machine combination. The sensing devices that measure the flow and the physical characteristics of all of the chemicals at all stages of the process can now report into a computer on a real-time basis, that is, as the process is taking place. The computer is programmed to expect particular relationships to exist. It also is told, however, that there will be natural deviations from these as the materials assemble and react and go their various ways and as valves open and close. The computer has equations stored in it that enable it to compute what new settings would be better in order to produce an optimum output, the most output per dollar in view of the variations that can be expected.

All of these interrelationships come from the chemical engineers who understand the process, to be sure. But if they were "on the line" taking down all of the latest readings of all of the gauges and thermometers and meters, and then attempting to reassess and compute what ought to be done, they would simply not be able to keep up when unaided by the computer.

THE IMPACT OF NEW TECHNOLOGICAL COMPONENTS

An illustration, that will also suffice as a summary of how advanced technological components are affecting systems design, is again found in our favorite example, the medical center. Here computers and other electronic devices can revolutionize many aspects of hospital design and operation. A good many tests can be handled on a semiautomatic basis with the results, say, from an electrocardiograph, going directly into the computer systems for storage and transmittal, with instant availability to the physician who needs the data or to research groups making fundamental studies. Simultaneously, the fact that the test was made can be made known to the accounting department, and a bill can be issued without intervention by man. Technological devices now can also automate many of the tests themselves—analysis of blood and urine and the like. Hospital rooms can be made much more efficient, providing much better medical care at lower price. More intricate beds, electronic observation of the room and of readings of the patient's condition at central points can be provided economically because of advances in technology.

The patient's heartbeat, temperature, breathing, and other conditions can be monitored by technological devices in the room and the result posted electronically at a central point, where continuous observation can be made so much more convenient and easy than now that the cost will go down, even as the health care goes up. In a similar way, the appearance of the patient, and the activity of the patient, can be monitored by television

THE IMPACT OF NEW TECHNOLOGICAL COMPONENTS

devices on a continual basis, improving nursing care and guarding against unanticipated emergencies.

The computer can do a better job of scheduling test facilities. The queue for the X-ray machine can be shorter. Patients can arrive closer to the time when the facility is ready for them, and yet the X-ray facility can be used with less down time. As indicated earlier, electronic-information systems for inventory control of the drugs and other supplies in the pharmacy can ensure the most reliable, speedy availability of all supplies needed in the hospital with the least investment.

All industrial, governmental, educational, and professional operations are coming to depend more and more, for operable systems answers to the increasingly higher capacity and speed requirements of today's busy society, on the introduction of new, technological systems components. It is necessary in planning any system, to call in a group of technologists who are experienced in applying the new technology to a host of applications. Many such specialists are members of good systems-engineering teams. Certainly, competent systems teams must include such advanced technologists, just as they must include the experts in economics, and other social sciences, in order to evolve a good systems design. We should not, however, make the mistake of assuming that because a group of people are good technologists they are broadly capable of applying the systems approach well. There are plenty of non-technological problems. Competence, imagination, and experience must exist to mesh the new technological

THE IMPACT OF NEW TECHNOLOGICAL COMPONENTS

component with the non-technical issues. It is only when this is done well that the systems approach is being properly applied.

CHAPTER XII

Applying Common Sense and Science to Civil Problems

Now that we have described the basics of the systems approach, let us look at specific examples of how the systems approach can be applied to produce effective solutions to civil and commercial needs of society. The pressures from shareholders on business leaders and from the public on governmental leaders to look beyond the norm for more responsible and responsive answers is now setting the stage for effective use of the systems approach for a wide array of needs and opportunities. In this chapter we present two quite different case studies. The first is a commercial problem—consumer credit data reporting to make feasible the “cashless” society. The second is a civil government challenge—the integration of a criminal justice system. Both examples illustrate how previously autonomous entities can be caused to cooperate harmoniously, using science and common sense to reach unique and superior designs of means to meet needs.

We start with an examination of the consumer credit data system developed by a systems team at TRW. In the United States, TRW became synonymous with credit data reporting, building what became a successful business entity at the billion dollar level. People became accustomed to talking about getting their “TRW” when

APPLYING COMMON SENSE AND SCIENCE

their credit status was checked or when a business ordered a credit check. Using the systems approach, TRW pioneered a new kind of credit data reporting, creating and maintaining the largest and most effective database for this purpose. This effort became the foundation for consumer credit activities in America. Once the system was established, credit grantors came to rely on a TRW credit data report to determine the wisdom of granting credit to individuals based on their payment history, earnings and obligations.

Today, we take easy access to credit data for granted. Thirty years ago, such access essentially did not exist. Today's students cannot imagine preparing assignments without the use of word processors and access to on-line information. It is also true that today's society cannot imagine life without the easy access to money, goods and services through credit cards and automatic teller machines. In the 1960s, a student felt lucky to have an electric typewriter and the credit card society had not yet been firmly established. Personal computers and the Internet were not yet available, nor was an infrastructure in place to support the credit-card society. Individual banks and stores granted credit to their customers, but none shared data with others, still less with gasoline station chains.

Then the changing consumer market—as it moved toward the cashless society—gave rise to a need for, and an opportunity to provide, an integrated system for credit data reporting. The resulting system came to cover the nation with low cost, virtually instantaneous records of

APPLYING COMMON SENSE AND SCIENCE

the payment history of millions of consumers and to provide other constantly changing, up-dated information on virtually the entire credit-using population. The application of emerging computer technology to consumer credit was accomplished by a systems approach based union of technical know-how with a commercial market opportunity.

Once the systems team formulated the basic ideas, they focused on the potential customers of such a system, the credit grantors, to determine their objectives and fundamental needs and to identify the alternative means for meeting them. The results of this exercise became the foundation for the system design. At the time the system was being conceived, no association of credit grantors, formal or informal, existed. Grantors of credit, such as banks, department stores, and gasoline stations, each retained records on individual's credit histories at their own establishments. They had no means or infrastructure to enable communication even if they thought to implement cooperation. How could they best determine whether to grant credit in the first place? Would it not be beneficial to know of individuals' credit payment histories elsewhere, their earning power, their disposable incomes? Without such information, countless businesses made incorrect and costly decisions as unreliable individuals went from establishment to establishment obtaining and misusing credit. Furthermore, the credit granting procedure, inadequate as it was in terms of quality and completeness, was also clumsy, time delayed and costly.

APPLYING COMMON SENSE AND SCIENCE

At the outset, in designing a superior system, the credit grantors could not be assumed to be hospitable to the idea of combining their resources. Always having maintained their own data, they felt it proprietary and confidential. It was up to the systems team to conceive of, assess and present the benefits a cooperating body of credit grantors could realize if they were in on the development of an integrated consumer credit data system. The systems team's innovations and analyses led to a convincing argument for collaboration for the sharing of data and the allowing of ready access to the data by the entire group.

Having articulated the objective of providing businesses with complete, accurate and constantly updated credit history for individual credit applicants, the systems team then set about to document in detail how the system would work so they could define the system's components. This imagining and synthesis went well beyond computer hardware and software requirements. In fact, before those elements could be adequately addressed, the team needed to come up with scenarios typifying the system's concepts in actual practical operation. Developing these scenarios required modeling the functions and flows of information, people and apparatus, and the system's interactions with the outside world into which the system must fit. The system designers had to ask a huge number of questions. What data were necessary for the system to meet its purpose? How often must data be entered into the system, and by whom? What is the output? How would the operators

APPLYING COMMON SENSE AND SCIENCE

evaluate the data? Who would have the authority to tap into the system and how and when would they access it? How precise must the data be? Is there a minimum tolerance for error? In designing the system, alternatives were listed for every action, every step of the way.

At the most fundamental level, the system designers could merely have chosen to automate the current processes—starting with regional credit bureaus and using computers to replace the clerks with their manila folders. That approach was eliminated early as not leading to a sensible design. A basic issue clearly deserved preference. That is, aside from how credit granting was done in the past, how should it be done now that we have new technology to handle information? What should we now set down as system requirements?

The use the credit grantors might be expected to make of the ability to access an integrated summary of credit history, their willingness to provide data, the data accuracy required, the flexibility of the data base, and the political and security aspects were all taken into account as the system design proceeded. It became clear that one rule had to be mandatory: to get access to the consolidated data set any accessor would have to provide its previously confidential data. Also, for the system to work, all the players, who had never before interacted, had to cooperate through a third party, the data base manager. The next important step then, in developing the system design, was to solve the problem of how best to involve the separate players, determining their

APPLYING COMMON SENSE AND SCIENCE

individual, separate needs, and convincing them that those needs would be met.

Though the customers of the contemplated system, the various credit grantors, were in many ways quite different, strong similarities were seen to exist as to requirements and contributions. An owner of a corner grocery store and a regional bank manager, both to benefit from knowing an individual's bill paying history, would each contribute records of payment to the central database. With such different sized businesses using the system, however, the designers would need to develop a mechanism to accommodate data entry differently from a range of inputs. Those inputs could be mailed-in records once a month for some, and magnetic data tapes supplied daily, or even more often, for others. Accessors would need virtually instantaneous responses in some instances while much longer waits could be tolerated in others. The systems team decided the system should be designed to "learn" as data were processed. For instance, if the system was set up only to inform of a credit risk if a certain dollar level payment was missed, then it would not necessarily identify individuals as credit risks if they missed several small payments. However, if the system were set up to provide feedback and to learn, it could identify that small missed payments could add up, and it would correct the data of the system to alert the credit grantor of a risk previously discounted.

Imagine now, that an integrated credit reporting system has been created for an individual city, the business owners in that city having agreed to pool their

APPLYING COMMON SENSE AND SCIENCE

information on their customers' bill paying habits. For an average size town of, say, 200,000 inhabitants, perhaps one-third to one-half of them would be adults capable of obtaining credit at one of more of the hundreds of existing establishments. This might result in recording tens of thousands of sales transactions per month. Extending the system to include all of the United States would require information on 100 million individuals. For all individuals, the system would store identifying information (for example, name, address, phone number, date of birth) as well as their income and credit payment histories. The data base would have to be dynamic, flexible enough to accommodate the constant updates as people act, travel, move, marry, change jobs and establish payment histories, good or bad. Ideally, the millions of credit grantors providing information and retrieving it would want to derive the benefits without having to greatly increase their workloads, change their processes, or incur additional expense for maintaining their records. The system would need to include a mechanism to allow the credit grantors to submit their information conveniently, accurately, reliably and economically and to receive reliable information back when needed.

Data accuracy was seen to be critical, the matter of precision having many dimensions. It would be a poor system that might assign credit ratings to the wrong individuals. Slip the names one notch on the continuum of millions of poor to excellent credit ratings and a chaotic situation would result. If the record is off by one

APPLYING COMMON SENSE AND SCIENCE

name, for example if Ramo becomes Ramon, then Mr. Ramo might undeservedly be the beneficiary of Mr. Ramon's excellent credit history. Or suppose a father and son both have the same name (do not add senior or junior), live at the same address, but have vastly different credit histories. A system requirement is to ensure that there are enough distinguishing characteristics in the identification data to guarantee that the system can distinguish and identify correct credit histories even with great similarities among them.

While it is very important that the right credit rating is assigned to the individual to whom it belongs, there are trade-offs between information reliability or accuracy and probabilities of mistakes. Designing the system to provide 100% accuracy in all data would require checks being put in place at data entry and departure every step along the way. In such a complex system, constant checking could cause the system to be slow in capturing, updating and reporting information. However, if safeguards are put in place to identify and account for anomalous deviations or accumulated small deviations, the requirement for 100% accuracy may be balanced by a suitably high probability that information is entered and reported correctly.

It was important to consider the political aspects of such a system as a design element. What were the implications of the storing and pooling of individuals' credit histories? What privacy issues might arise? The system design should minimize the negatives that might cause the government to pass laws that conceivably

APPLYING COMMON SENSE AND SCIENCE

might prohibit centralized data collection. A process was seen to be needed to address circumstances in which an anomalous bad payment record resulting from an excusable lapse, could be rectified and the bad credit rating cleared. Those denied credit as a result of a bad credit rating needed to be given access to their credit report. They had to have a chance to rectify the situation. In addition, as a part of the overall system design, the team needed to create appropriate application forms to obtain credit seekers' permission to allow the grantor access to their data.

The systems team also had to design for security. Only authorized users (the credit grantors) should be allowed access to the database. The system design needed to incorporate safeguards to protect the individuals, much like the "two key" system for safe deposit boxes in the bank. The system should require more than one source to enter negative information and to cause that negative information to affect the person's credit worthiness.

A major decision dealt with whether the system should incorporate the passing of judgment or merely report the data. In the end, the team designed the system to provide such information as would allow the credit grantors to come to their own conclusions about the risk of granting credit to individuals.

Once the systems team determined and addressed these basic operational parameters, the hardware and software could be designed and the system's operational characteristics could be modeled and analyzed. The communications element was important. By what

APPLYING COMMON SENSE AND SCIENCE

network of apparatus would the users access the data? How in terms of machines and connections would the database be searched? How are data to be organized and updated? What would be the best time to input data obtained from credit grantors? What credit application forms would most facilitate data input?

As the systems team developed the credit data system, it integrated many established and emerging technologies to provide a practical and profitable solution that we now take for granted. Credit grantors today can access a consumer credit system that will quickly inform them how well an individual has managed his credit. That credit report is a compendium of all credit transactions from the participating organizations, and is based on a powerful and extensive database. The systems approach provided a logical and objective system design to enable the growth of the credit industry as the world moved into the cashless society and became more interconnected.

Let us now turn our attention to an entirely different application, one with very different challenges, but one to which the systems approach is equally suitable. A great problem of society worldwide is that of managing crime information. The existing criminal justice system, is too often unable to identify adequately the individuals taken into custody, provide timely information on their criminal history, establish linkages between crime and criminals, classify inmates properly when they are incarcerated, and to notify victims when an offender is released on bail. Many criminals know the weaknesses

APPLYING COMMON SENSE AND SCIENCE

in the system and take full advantage of them. Lacking an appropriate system of modern design, crime information is generally handled poorly, uneconomically, and with extremely limited value in curbing crime.

That change is constant in our world applies also to crime. Organizations have existed almost since the beginning of civilization to address crime issues and processes ranging from preventative (the making of laws and enforcing them), to restorative (a victim oriented system providing punitive and rehabilitation processes). The problems facing modern criminal justice systems are in great part the result of the very advances in our technological world in the past one hundred years that have made our societies more mobile, sophisticated and fast paced. When the world was turning more slowly, it was effective to maintain the autonomous relationship among the participating criminal justice organizations provided in our constitutional system of government. Now it is becoming increasingly important for all the elements of the criminal justice system, if they are to keep one step ahead of the criminals, to join forces, share resources, become proactive and employ tools that technological advance makes possible.

How can technology and augmented communication among previously autonomous entities, come together through the systems approach to address the problem of crime? One way, now gaining increasing support, is to develop and test an “integrated” criminal justice system. In brief, an integrated criminal justice system is one in which all the organizations having a role in criminal

APPLYING COMMON SENSE AND SCIENCE

justice (police, courts and corrections) cooperate in unprecedented ways to share information on crime and criminals effectively. The systems approach can be used to streamline the processes, structures and information as to enable a proactive rather than a purely reactive criminal justice process and possibly transform the operation of the criminal justice system in a fundamental way. Using information technology in a properly designed integrated system can provide quick, accurate and consistent access to the information required to make well informed and appropriate decisions about an offender. Mistakes, such as incorrectly releasing individuals, come about because the decision maker lacks timely access to needed data on the arrested individual, such as outstanding arrest warrants. If, for example, the suspect is rapidly and accurately identified through a search of an automated fingerprint identification and processing system, it will be known while the person is still in custody whether he or she has been arrested previously or has an outstanding arrest warrant or subpoena. This information is critical in determining whether bail should be granted by classifying individuals in a process similar to credit scoring (low to high risk), for setting the security level in which they should be kept in a detention facility. The information will also ultimately be of key importance to the prosecutors as the case goes to trial.

A critical consideration, as the systems team faces the customers of the integrated criminal justice system, is to recognize that each of the participating organizations

APPLYING COMMON SENSE AND SCIENCE

typically has a degree of legislated autonomy and uses processes established to accomplish its own missions. While almost everyone recognizes the need to cooperate and can see the value in integrating their information services in support of the various law enforcement, prosecutorial, court and correctional services provided within their jurisdictions, giving up autonomy can be difficult. To make things even more challenging, this grouping of government entities, that should cooperate in ways not previously attempted, will have to include more than just the directly participating agencies. Also involved will be various funding agencies, non-governmental agencies and private organizations such as those of attorneys. These organizations will also have certain new requirements to meet. To design successfully, the system designers must cause the large inclusive group of agency representatives to come to hold a common vision of the scope of the project. The systems team certainly must be highly interdisciplinary, incorporating expertise from criminal justice, law, technology, group interaction, policy, legislation, financing and process and information systems modeling.

Once the customer and systems design team have agreed upon common objectives, the systems team can commence to detail the scope of the integrated criminal justice system they hope to achieve. The objectives will gradually be refined into requirements for the system design. In turn, these requirements will gradually be turned into specifications for system components. The

APPLYING COMMON SENSE AND SCIENCE

systems team having identified the functions of the envisioned integrated system, then identifies the elements that will provide the required functions. For example, if one objective is to ensure that complete and accurate information about an individual offender is available at every step of the process, derived requirements might include an automated fingerprint identification system, a central records component, a notification subsystem, and the means for data interchange among these components.

One of the first steps in detailing the processes to be included in the system design is to examine the function and flow of information, people and materiel of the current system now in operation. The current in-use processes have been getting the job done after a fashion, and are likely to have varying degrees of automation. Particular note needs to be made of where the efficiencies of the current process cannot keep up with the high-tech criminals or where resources are ineffectively used. Thus, in the current process it might be that when an individual is arrested, his fingerprints are taken using an inkpad and a specially prepared card. However, because the current systems maintain past fingerprint cards in filing cabinets, it could easily take weeks to obtain a positive identification of the individual and past criminal record information about that criminal. Knowing this, criminals often give false names and count on being released on bail, when in fact, they are wanted for a number of other crimes. An automated fingerprint identification system can query a central

APPLYING COMMON SENSE AND SCIENCE

database and, within minutes, return a match if the person has been previously arrested. Automation can facilitate decision making in many other ways.

Similarly, the systems design team will model the current processes used by the law enforcement, judicial and corrections agencies observing when and how information about an offender is passed from one agency to another, the individuals involved, and the tools used. Collecting information on current processes is a necessary step to determine the critical activities and information interface points. A typical case will be “walked through” the current process and the team will note where particular agencies need information and when that information becomes available. At each point in the operation it will be determined what the data needs are, who the individuals are who need information, and what information needs to pass on to the next step.

An understanding of the current processes thus enables the organizations participating in the criminal justice system to envision the new, automated system. Throughout the analysis, this question will be continually asked: If we did not have the constraints of an “in-place” system, how might we better accomplish the task? Can we put computer terminals on the benches of all judges so they can have immediate, complete and current information on the case before them? What is the efficient way to keep track of an inmate in the correctional facility? Is the inmate an escape risk? How best might we access the necessary information from

APPLYING COMMON SENSE AND SCIENCE

each of the agencies? Is it possible to develop a truly useful central database? As with the credit data example described earlier, the systems team will propose a series of alternative approaches from which flow diagrams can be developed and the processes modeled as steps in selecting the most attractive options. Systems experts will simulate or model the workings of the proposed system to observe the simulated performance of the complex system consisting of a large number of complex relationships and data. The overall performance thus can be modeled, but the human intuition, judgment and decision making of the individuals who work with the current systems must be taken into account as a “reality check.” The most modern systems are ineffective if the man-machine interface is not geared to the needs of the user.

The advent of powerful, robust and fast information technology makes possible a breadth of functionality never before conceivable or available. In most cases, indeed, each of the agencies will have some kind of computer systems already in place, their so-called “legacy” systems. The team designing the new system will want to consider the appropriate continued use of piece-meal units as components in the proposed new integrated system. First, the team must assess the current operating systems. How do they store data? Are the present system components compatible among the agencies? What is the infrastructure supporting the system? As is likely, the individual agency-level applications will be run on different equipment using

APPLYING COMMON SENSE AND SCIENCE

different, often custom-made software packages. Even so, can the integrated system, retaining these legacy items, be enabled to share information? If the cooperating agencies agree on a resulting integrated system that requires new hardware and software, how will they pay for it?

The final system design interacts as to its objectives and strength with the economic, budgetary base, both as to initial cost and maintenance. Make the new system design too extreme in its scope and no practical way of funding it may exist. The team will also prepare development schedules and plans to go with each candidate approach to designing and installing the integrated system. Here again some interactions among the new and old need careful attention. For instance, the agencies cannot allow the current systems to be turned off while the new system is being developed and prepared for installation. The systems team must help the organizations participating in the criminal justice system to put a plan in place to allow work to go on while the new system is being phased in. This plan will address not merely the new integrated environment, but also the special interim and final needs of each contributing agency.

Integrating a justice information system clearly poses many different challenges, but the systems approach provides a way to address all the issues if the approach is carried through combining true practicality with well chosen sophistication.

APPLYING COMMON SENSE AND SCIENCE

These two examples illustrate the broad applicability of the common sense and science embodied in the systems approach. New technology provides great opportunities for superior solutions to the needs of private sector and government agencies. Co-operation is an essential element in the application of the systems approach in today's environment. If there is adequate willingness to work together among government officials from different agencies, or private sector groups, the benefits can be enormous.

Bearing these examples in mind, let us now take a look at the future of the systems approach.

CHAPTER XIII

The Future of the Systems Approach

INSOFAR as the systems approach merely represents use of objectivity, logic, and automated common sense, it seems inexcusable not to use this approach, whatever may be our problem. But it isn't quite that simple. Actually, the "formal" use of the systems approach, the engaging of a team of experts in systems engineering, the dignifying of both the problem and the methodology that is implied when the systems approach is consciously brought into play—these concepts can easily be misapplied. At least, they can be misunderstood, oversold, leading us to unsatisfactory proposals for handling problems and doing disservice to the understanding of what the systems approach is all about.

Let us take, as an example, the question of how big a problem one really should surround with the systems approach. You start out to plan a new hospital, for example, and you have to think in terms of changes in the practice of medicine, changes in governmental approaches, the politics of medical care programs, changes in the affluence of the society, and the population growth in the area. There are so many problems that seem at least highly significant, if not dominant, in determining the of answers we should be coming up with, that, if we really want to be complete, we have to predict the future for the population of the

THE FUTURE OF THE SYSTEMS APPROACH

hospital's entire geographical area. But this area ties to surrounding areas and to the nation, and the nation ties to the world. The systems approach, carried to an extreme in seeking to cover all interactions, can be absurdly ambitious and impractical.

In fact, embrace the problem too broadly and you will not only get nowhere in its solution, but you will be doing a terribly poor job of systems engineering. After all, optimizing is one of the concepts included in the systems approach. And it is hardly an optimum attack on a problem to overly define it and require billions of dollars and twenty years to assemble all the facts.

A skillful team applying the systems approach—and this applies to the technological as well as to the nontechnological or social factors—will close in on the problem. The team will consider interactions with outside factors, only to a practical and sensible extent. The weight and focus will be on those aspects closer-in and most significant. As the issues are categorized and some are seen to be less direct, they will be dealt with in a more gross and more superficial way. This is not only of necessity because of a lack of adequate knowledge about all of these other factors, but also because otherwise the systems team will make no headway.

But are there not problems of great importance, where the systems approach is indicated, but where the problem is inherently too big to justify the systems approach? Let us take a very good example to discuss this question. Let us take the entire economic system of

THE FUTURE OF THE SYSTEMS APPROACH

the United States. To get at some interesting points here, let us consider two different sides of this question.

On the one hand, we can say that though the problem is huge, it is indeed a system. It is a complex of people, things, equipment, information, matériel, and money flow, all involved together in an extremely large interconnected network that, whether we like it or not, determines the economic life of the nation. The system is there. It exists, designed or not, analyzed or not.

And to this we can add one other easy conclusion. It has apparently become essential—at any rate, it is now accepted practice—that the government of the United States seeks to affect this system, to adjust it, speed it up, or slow it down. This practice is acceptable, presumably, to the majority of voters (though not all); and it comes about because of a feeling that the government is in a unique position to do some controlling that ought to be done. Generally speaking, we all want freedom from severe business cycles, recessions, and periods of boom and bust. We also want control of inflationary forces, low unemployment, and a sound dollar. The government can influence these things in several ways. It can modify government expenditures, control interest rates and money supply, alter taxes, assign priorities, put controls on the production of many things, stockpile materials, modify tariffs, assign rates to utilities, arrange salaries and benefits for millions of government employees, determine the marketability of gold, determine the use of resources, set minimum wage rates, locate government facilities in different parts of the country, set schedules

THE FUTURE OF THE SYSTEMS APPROACH

and routes for airlines, influence labor-management negotiations, and take many other such actions.

The economic system is a system in every sense of the word, and it is indeed being directed substantially in an effort to achieve such workings of the system as will meet various political objectives.

Now, we notice that whenever there is something unsatisfactory about the system, such as too high an inflation rate, too high an interest rate, or a threat to the dollar, then there are immediately wide differences of opinion among the experts, in and out of government, as to what steps the government should take and what the effect of those steps would be if taken. It would be nice if we could set up a model of the entire system on a computer that is of such capacity and so programmed that it could handle a very accurate and complete mathematical simulation. In this way we would be able to work out ahead of time exactly what to do, and we would know its effect before we did it. We could compare alternative actions. We could choose the course most suiting our objectives. There would be no arguments as there are now, because everyone would believe and accept the "complete, logical, optimized" answer that results from this full application of the systems approach.

Alas, this is not possible. First of all, we are nowhere near a position to be able to gather all the pertinent facts. To assemble even a small fraction goes beyond our means today for observing, recording, and processing. This is too big a system. We would almost have to get

THE FUTURE OF THE SYSTEMS APPROACH

down to the individual contributor, each man and machine. Even if we were to conjure up by magic all the statistical data, our goals are far from clear. Also, we do not understand sufficiently the basic relationships among inflation and unemployment, minimum wages, interest rates, taxes, etc. So our understanding of the system's working is inadequate.

There is, however, another viewpoint which, like the one we have just cited, must be rated as debatable (and oversimplified in the amount of description that we give it here). It amounts to our saying that while we do not have all, we have part of the needed information. We do understand partially, though granted not totally, some of the relationships among the main factors.

Economists have made considerable progress in the last hundred years and the computer has been applied to the handling of important economic data in recent decades. Moreover, attempts are being made with success to relate many of the main factors to one another, to set up mathematical models, and to use these models to predict next year's gross national product and other economics results as a function of varying assumptions of governmental and other action.

Skillful systems teams can therefore provide us now with solutions to parts of our problem with a quality of logic and objectivity that we should not overlook, or fail to make use of, merely because we cannot as yet handle the entire problem. This point of view, in other words, says: You have a system that is vital to you, that exists whether it pleases you wholly or not, whether you

THE FUTURE OF THE SYSTEMS APPROACH

understand it completely or not, and that you are already forced to influence by action. Thus, you should certainly prefer logic to illogic, fact to guesswork, and objectivity to emotional and political hunches and drives.

From this point of view, there is no such thing as a system that is too big for the systems approach, just as there is no epidemic that is too big for the useful practice of medical skill. The fact that total success is as yet beyond us does not mean we should throw away the tools that can give us partial assistance.

Fortunately, most of the real-life problems that are asking for solutions today are considerably smaller than the entire world economy. It is possible, as a practical matter, to isolate pieces of most big problems and arrive at conclusions useful enough for us to say the systems approach pays off. If we are looking at interurban transportation among several large cities we don't absolutely have to predict completely the changing habits of the people into the next century. It is still useful to us to be able to compare five or six ways of moving people about in that area, and to see whether under any set of circumstances that we can imagine for the future, some basic approaches seem superior to others. We can at least have that part of the problem analysis as a guide toward making better decisions.

A final important limitation of the systems approach deserves discussion. It is the handling of the "unknown" factors—weighing the importance of human reactions, for example, or guessing political influences, or generally dealing with nontechnological issues that lend

THE FUTURE OF THE SYSTEMS APPROACH

themselves little to measurement and quantification. Oftentimes, basic data that are available in theory are unobtainable in practice because it would take too long or cost too much to acquire them. This shortcoming constitutes not merely a limitation, but also an opportunity for confusion and incompetence in use of the systems approach and an excuse not to use it when it might really be helpful.

Narrow but overly enthusiastic systems engineers, for lack of available information on some facets of the problem, may become enamored of the quantitative, tangible, perhaps technological ones. They will assume something about the unknowns and proceed to put those assumptions far back in their minds. They may optimize only the relationships of those parameters they can relate and yet claim a proposed design as "optimum"—this even though deviations from their assumptions about the unknown parameters might cause a significantly different design to be superior.

The right procedure is to apply the systems approach competently to complex problems, seek to get the facts, use the analytical tools where they apply, and add wisdom and flexibility of choice to the decision-makers who should inject, for integration with the rest, the best assumptions about the nonquantitative factors that their unfettered and enhanced judgments will permit.

We indicated in the very first chapter that the public is ready for the systems approach and that the professionals are beginning to be available so that it can be put to use in practical problems. We are not yet at the point where

THE FUTURE OF THE SYSTEMS APPROACH

this approach is being broadly used. We are not set up for it, as applied to the big social-engineering problems of our society. What is true is largely that we now know we have problems and we want to see them attacked. We also appreciate that there is a technological ingredient in most of these problems, and we are recognizing that if technology can be properly synthesized with considerations of a non-technological nature, with the factors of economics, sociology, and political forces, then we might have a new and superior tool for going after these problems.

How do we break away from the present pattern of fragmentary, embryonic efforts, spottily applied here and there, and rise to a heightened activity somewhere near what is needed in total attack to meet the problems in a timely way? One answer is to note that the systems approach itself contains within it the elements for furthering its own use. The systems approach is a bottleneck-breaker. The more it is used, the easier it is for it to get used.

Thus, the systems approach is often a first step in answering the question of how much money is needed. It helps to articulate the goals that might have been only crudely understood before. If systems work is done competently, it is inherent in it that it is logical and quantitative as much as is truly possible, and it provides comparisons. You know what you will get for what you pay. When the preliminary systems studies have been made, it is probably apparent that the cost savings, if an optimum design uncovered by the analyses is chosen

THE FUTURE OF THE SYSTEMS APPROACH

over an ordinary design, will greatly exceed the expenditures to make the studies.

Starting with the acquisition of all of the facts, a systems effort describes performance, cost, equipment, matériel, and information flow patterns, and the people required to work at prescribed, defined tasks. It shows how the proposed system integrates with the existing operations of real-life society. Accordingly, the systems approach, when applied properly, answers a good many questions for all involved in decision-making, whether they be government officials, business executives, hospital heads, voters, or professional participants. Some must decide on public or personal stands to take; others will need to make commitments on risking capital to start the development of the equipment that might be marketable to go into the system; still others will have to conceive of how the system will fit into the present society.

The pace of the application of science and technology to the big third area of society, civilian systems, oftentimes is bogged down because the problems are so difficult, complex, little understood, and controversial, and involve so many semiautonomous groups with selfish interests. Many times nothing can be done unless a new level of objectivity reached. The possibilities must be laid out from a platform of adequate breadth in consideration of all the factors and adequate detail as to the criteria for judging alternative approaches. Solid specifics as to what the choices are, and what will be the

THE FUTURE OF THE SYSTEMS APPROACH

consequence of choosing these various choices or doing nothing at all, must be brought out.

So, perhaps in the end, the systems approach will be most useful because it will encourage and make possible action. We badly need that encouragement in a society of people who must, in majority, move along together in their thinking, approval, interest, and appreciation before such action is possible. In fact, we are today controlled too much by crisis action; nothing gets done until a problem has reached crisis proportions. Then we are likely to go off in a frenzy. The habit of the use of the systems approach, if we can acquire it, will provide a steady flow of clues to predict and forestall cataclysmic effects of inaction.

The systems approach should militate for social advances, for decisive implementation to solve our problems in still another way. The systems approach suggests organizational innovation, and such innovation is usually required in our social structure if we are to handle our unsolved problems. The systems approach, in showing the interconnections between various aspects of a problem and in bringing these together into appropriate tradeoffs, compromises, and optimizations, automatically lays the foundation for the system's implementation. A practical systems approach to any truly existent problem contemplates implementation to solve the problem after the analysis and synthesis have taken place. It also points out how the interacting factors must be kept under control by proper reporting and decision procedures.

THE FUTURE OF THE SYSTEMS APPROACH

Thus, it might be that a systems approach would show how to un-pollute a major river into which many cities pour refuse and whose waters are used in various ways by the industries and population along its banks for a considerable distance. The systems approach would show what can be done, what it will cost, why it is beneficial, and would consider all the negatives, such as the need for moving certain industrial operations. But it also would include the relocation expenses, and in so doing it would contrast the bad effects, such as the dislocations with their cost and impact on human lives, with benefits to those same human lives. Now, if all of these things have been considered on a thorough and objective basis, and if the people of the area in considerable majority wish to go ahead and implement the steps that are called out, then they obviously need an organization that has the power to do so. They are led by this previously unavailable understanding to the idea of modifying existing organizations or creating new ones. They are led, moreover, by the systems approach to see what kind of organization, with what powers and responsibilities, over what aspects of their society, controlled in what way, must now be created if they really want to get on with the solutions. In a sound beginning way, this is happening already with some water basins being defined and regional commissions being created.

It is not very helpful to make a systems analysis showing how much smog is produced by automobiles, and how this could be changed, unless, since the

THE FUTURE OF THE SYSTEMS APPROACH

problem is that of an area covering many cities, there is going to be some kind of legislation, binding on the whole area and not just on one component city of the area, to implement the rules, regulations, and practices that are required. A systems study of the smog problem in an area is not competently carried out unless its results make evident what rules and control organizations are needed. Again, we see beginnings in the United States; some one hundred air quality regions have already been defined.

Now, how long will it take for the systems approach to be developed fully, to be applied widely, to be effective in pointing the way toward action, to assist in clarifying goals, and to guide us to organizational modifications in our social structure so as to make full use of the powers of science and common sense? It may well be a decade before we can say that the systems approach is being applied on a large scale to alter the balance between technological advance and lagging social maturity. In ten years, the battle might well have been joined, the contest being between the growing need, on the one hand, and the application of the scientific systems approach to the areas of civil systems, on the other.

In ten years, the public, governments, the people of influence in industry and in science and technology, may all be mutually convinced of the importance of a good systems approach, by whatever name. At about that time we shall notice the appearance of a new bottleneck, and this will be a shortage of good systems engineers. In saying this, include of course, as always, not only the

THE FUTURE OF THE SYSTEMS APPROACH

technologists, those with the conventional engineering or physical-science specializations, but also the non-technologist members of the team, the economists, the political scientists, psychologists, experts in education, etc. In a decade we shall certainly have plenty of systems-approach teams ready to work on any problem that comes up. We are seeing the beginnings of that now. But outstanding competence in the teams is another thing. The work is difficult. The assembling of the technical and non-technical experts into working groups that have the combination of imagination and wisdom cannot expand as rapidly as would be desirable. Also, the tools of the systems expert must be extended. Perhaps the narrowest constriction in the bottle's neck that will limit the flow of useful systems analyses and designs will be our limited ability to measure, simulate, and test systems and system elements that depend on the reactions of human beings. We shall have to develop better ways to tap preferences, judge needs, present possibilities, and evaluate alternatives for the many systems and parts of systems that relate directly with or are dominated by the human factor.

Still, it would be nice to imagine that period ahead, when the only thing that stands in the way of the fullest application of the systems approach is that we lack enough trained professionals. That will be the beginning of the golden age. Once most people are wedded to combining science and practical common sense to create solutions to society's problems, the world is going to become a lot better.