RALPH EDWARD GIBSON

A SYSTEMS APPROACH TO THE MANAGEMENT OF RESEARCH AND DEVELOPMENT[1]

INTRODUCTION

Some twenty years ago I gave a number of lectures to groups interested in the administration of research, stressing principles and policies rather than management details. The contents of these lectures were published in three parts in the journal, *Research Management*, under the general title, "A Systems Approach to Research Management."[2]

In planning the curriculum for the course in "Organization Dynamics" given to certain members of the Senior Staff of APL, Drs. A. Kossiakoff and R. J. Thompson suggested that the substance of the old lectures would form an appropriate topic for the introductory lecture of the course. I accepted the invitation but soon decided that, whereas I felt that the material as originally published was still very pertinent, a new method of presentation and a change in emphasis were in order. Thus in the following pages I shall depart markedly from my earlier treatment of the subject. For instance I shall discuss the roles of management and the setting of objectives in terms of one diagram instead of three, shall infer, but not discuss in much detail, many factors that contribute to the strength or debility of a research organization, and shall deal more explicitly with human communications.

SYSTEMS

The words "system," "systems" and "systems approach" are widely used and abused. I must, therefore, say what I mean when I use the word "system." I define a system as *an assemblage of elements* (*entities*) *which cooperate to achieve a certain defined* (*often predetermined*) *objective.* In this definition the elements may be many and varied. For instance in an antiaircraft guided missile or a navigational satellite, the elements are mechanical, electrical or chemical in nature and fabricated to order; in the human body, cells, fluids, nerves, muscles, etc. have evolved as elements of the system; in an R&D organization, or for that matter any organization, the people with their many diverse aspirations and characteristics are the elements. Saint Paul, (I Corinthians, 12:12 ff), drawing an analogy between the Church, an organization of people, and the human body, a "biological" organization, gives a good description of a system.

There are two very important words in the above definition, namely, the words *cooperate* and *objective*, for without the implications they convey, an assemblage of elements is not a system. In order to *cooperate*, each element must base its individual actions on an exact knowledge of what the other elements are doing. In more formal words, each element must be able to generate information and communicate it to others with timeliness and exactitude; furthermore each element must be able to receive and interpret communications from others and act appropriately with timeliness and exactitude. As a further requirement of cooperation, each element must know that its message has been received and appropriate action taken. Direct and feedback communication links are essential in any system.

The *objective* of a system, the achievement of which is the purpose of all the elements, is, it goes without saying, a most important word in the definition, and indeed, the choice of objective really determines the viability of the system as a whole. The objective also sets the criteria for distinguishing between the correctness and the incorrectness of the behavior of the elements of a system. If the output of an element contributes to the achievement of the objective it may be called *correct*. If it does not, the word *incorrect* may be applied. From this point of view, the value judgment distinguishing between correct and incorrect behavior, right or wrong, cannot be made in an absolute sense. What may be correct behavior in one system may be incorrect in another, depending on the objective to be achieved. For example, the management of a company, whose avowed objective is to make money for its stockholders, may justifiably conclude that a division of the company that chronically loses money is finding incorrect answers to the questions it has to answer. Remedial measures are indicated. On the other hand, if, as in a university, the main objective of the system is the education of men and women to be leaders in disciplined and imaginative thought and action, the monetary profit or loss generated by a component (department) is only a very secondary criterion of its performance. The questions to which it must find answers are much more sophisticated, and the assessment of correctness or incorrectness of their answers requires rare judgment and wisdom.

Thus the title "A Systems Approach to the Management of Research and Development" invites attention to *cooperation*, the generation of information and the communication links that convey it from one element to another, and the many complex factors that create or destroy cooperation and also to the *objectives*, how are they determined and who determines them.

I should note here that we must distinguish two types of system, the "closed system" and the "open system." The closed system contains within itself everything needed for its continued operation. The only example I can think of is the Universe (and this almost by definition). The open system depends on something outside itself for its lifeblood and all systems we work with are this kind. For example, the large industrial research and development organizations like General Electric, Union Carbide, or that outstanding R&D organization, the Bell Telephone Laboratories, depend on outside sources for their input and acceptance by the general public for the value of their output.

INTELLIGENCE

In a very interesting and provocative book filled with unconventional ideas, J. E. Lovelock[3] makes the following statement: "Even at the most rudimentary level, the primitive cybernetic system discussed (a thermostatically controlled oven) which provides the correct answer to a simple question about the internal temperature of the oven, *requires a form of intelligence*. Indeed, all cybernetic systems are intelligent to the extent that they give the correct answer to at least one question." From this statement, I would suggest a definition of an intelligent entity. *An entity, the element of a system, is intelligent if it can find the correct answer to one question and act accordingly*. According to this simple definition, a thermostat is intelligent if it can find the answer to two questions: Is my environment too hot or is it too cold? It can take appropriate action to cause reduction or increase of the environmental temperature as required. An amoeba is intelligent; it can find correct answers and take appropriate action to ensure its survival. An enzyme is very intelligent. The sea slug, *aplysia*, not only can find correct answers to many questions, it can also learn by experience. The chief difference between the higher orders of intelligence, as in man, and the lower orders of intelligence, for example, in *aplysia*, lies in the number and sophistication of the questions that can be answered correctly and subsequent actions taken.

I like this definition for a number of reasons, one being that it emphasizes the continuity in the evolution of man from the very beginnings. We do not have to ask if a dog is intelligent, if a worm is intelligent, etc; all are, to a greater or lesser degree, a degree measured on a logarithmic scale.

This definition leads to the concept that intelligence is what makes highly improbable events happen. Maxwell's demon, by finding correct answers to questions raised by the speed of molecules, could take action that decreased the entropy of the system. Generations of men had to find correct answers to questions posed by nature before the probability of an event originally measured in large negative powers of 10, namely Apollo going to the moon, became unity. I must say that there are many people whose knowledge and judgment I respect who do not share my views and, indeed, to whom this simple definition of an intelligent being is absolutely repugnant, but they have not yet advanced an alternative of comparable simplicity.

The systems approach to R&D management is, therefore, an intelligence approach; if we are able to find and implement correct answers to the right questions, it may even be an intelligent one.

THE R&D ORGANISM

I use the word *organism* in preference to *system* to emphasize that we are dealing with an open system, and in preference to the word *machine*, which may imply to some a rigidity of mechanism which makes adaptation to changing circumstances difficult if not impossible.

Figure 1 shows diagramatically what we might call the skeleton of the organism. The tissue, blood, muscles, and nerves are composed of people. The inputs are all products of the human mind and will. Curiosity about the world around us, converted into intelligent questions, initiate the organism's operation. Industry, imagination and skill keep it going. It is fed by the knowledge and understanding inherited from the past, living in the minds of people and transformed by their imagination. Its objective is the extension of valid human experience and the use of this experience to improve the survival probability of mankind.

In Fig. 1, the shaded boxes represent activities or operations; those outlined in black signify results or

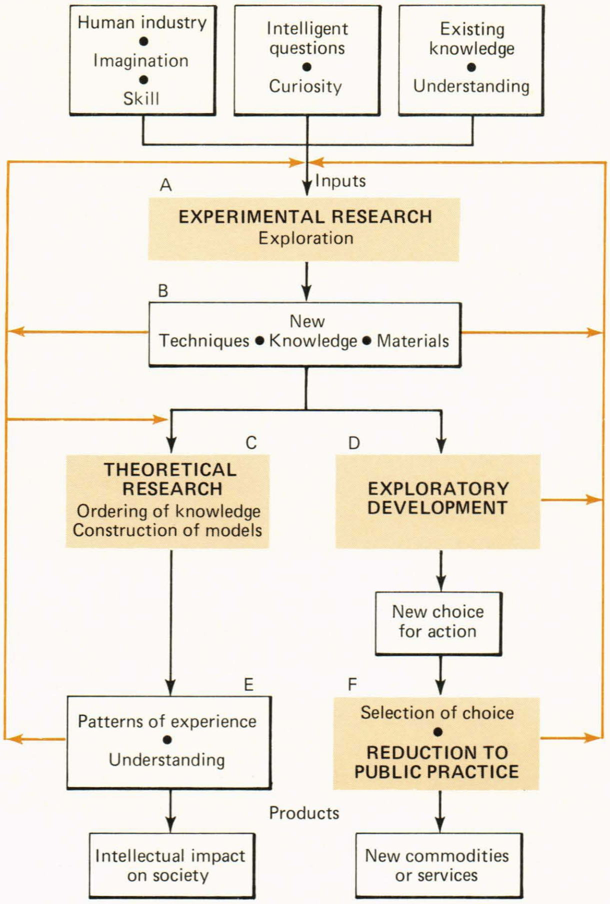

Fig. 1—Scientific research and exploratory development.

products of these activities. The black lines represent the direct flow of ideas, the colored ones represent the feedback of ideas.

Box A (Experimental Research) represents all those activities directed towards obtaining first-hand exact knowledge of the workings of nature. It is the province of the research scientist, the inventor, the amateur, as well as the professional observer of natural phenomena. The inspiration for this activity comes from various sources, not only the boxes labelled "Inputs" but through the feedback lines from problems arising in the results of theoretical studies (Box E) and practical engineering or clinical problems uncovered in Boxes D and F. I shall not attempt to describe the effort and ingenuity involved in the activities in Box A because long experience has convinced me that if a person has not actually done experimental scientific research, he or she can never really understand what this term means; and, if a person has experienced the discipline, frustrations and triumphs of adding one valid fact to the sum total of human knowledge or a new choice for human action, there is no need for me to describe it.

The products of Box B (New Techniques, Knowledge, Materials) may be used to form grist for the mill of the synthesizer, the person interested in ordering valid knowledge into an aesthetic pattern or mental model of nature which accomodates all valid human experience and from which new facts may be predicted. To use the analogy of *The Builders* given by Vannevar Bush in a poetic essay bearing that title[4], the workers in Box A quarry and polish the stones with which those in Box C build the magnificent edifice called modern science. I should note in passing that the same individual may work in Boxes A and C.

The feedback loop (Boxes A, B and C), involving the products of theoretical research in Box E, is probably the most important feature on the diagram. I have called it the Claude Bernard loop, the interplay of "Experimental Practice" and "Experimental Theory." For until there is complete agreement between new facts and theory, both are suspect. Facts may be contaminated by irrelevance theories or by inconsistency. When purification of one or both results in reconciliation, the loop contains positive feedback and knowledge grows exponentially. When, however, a discrepancy exists, the positive feedback ceases and stagnation sets in. A classical example of this is the discrepancy in the estimation of the age of the earth as computed theoretically by Lord Kelvin on the basis of physical theory available at the time and the age requirements posed by the empirical facts gathered by the naturalists. The discovery of radioactivity eliminated this impasse.

EXPLORATORY DEVELOPMENT

New knowledge, techniques and materials have always been grist for the mills of the practitioners of the useful arts, the engineers, the clinicians and all others who, sensing the needs or desires of their fellows, search for new choices for action and new commodities and services for society at large, usually but not always with a view to profitable recompense. Throughout the ages up to the 19th century, the practitioners of the useful arts had to supplement the unsystematic current knowledge by discoveries of their own, the results of many trials and many errors. When they found a correct answer that enabled them to reduce their ideas to practice, they realized that they possessed something so valuable that it had to be kept secret, and so grew up a large number and variety of "trade secrets," the exclusive property of families or guilds.

With the growth of systematic scientific knowledge and the research to extend its boundaries, new knowledge, techniques, and materials increasingly became public property, and the profitable application of the brain children of the inventors came under the protection of patent laws based on either priority of invention or priority of disclosure.

The right-hand branch of the organism has, therefore, had quite a long independent history, but since the days of the early developments of electricity for industrial purposes and the marriage of organic chemistry and the dye industry, it has become more and more closely integrated into the R&D organism. It is worth emphasizing that it is through this right-hand branch, and only through this branch, that scientific ingenuity, imagination and skill contribute to the *material* progress of mankind.

Box D (Exploratory Development) represents the activities that demonstrate the complete feasibility of new "choices for action" that arise from the availability of new knowledge, techniques and materials. These choices are usually embodied in prototype devices or experimental protocols or procedures for services. At present, Box D is the seat of the early states of a development in "systems engineering" (using the phrase in its broadest meaning). Even a vague description of what goes on in Box D would occupy many pages, so I shall merely say that this activity introduces extensive teamwork involving people trained in many disciplines. It involves to a varying extent the coordination of leadership and documented communications. It involves sizeable expenditures of funds and introduces the importance of time scales because the value of a new choice for action depends on the timeliness of its availability as well as its ability to satisfy a public need.

Box F (Reduction to Public Practice) comprises all those activities that convert the prototype devices, commodities or services from Box D into useful, reliable products that the customer will buy. First and foremost is the selection of the new "choice for action" to be "engineered for production," a decision which taxes the ability of management to the utmost and, indeed which distinguishes the good manager from the mediocre or poor one. This decision involves the long-time commitment of resources, the expenditure of money, and the efforts of many people toward a specific objective, the *a priori* probability of whose achievement is never unity.

Considerations which enter into this decision include a realistic analysis of the customer's needs and the ability of the prospective product to fulfill these needs, the costs of production, the resources of the organization to produce a reliable product on time and at an estimated cost, a consideration in which the state of the *prevailing technological environment* plays an important part. By technological environment I mean the products of previous developments that have been reduced to public practice. This comprises the sum total of all the know-how, skills, techniques, tools, materials and appurtenances that are items of commerce, available for producing a new device or perfecting a service so that it can be presented to the using public in simple, reliable and economic form.[5]

The activities in Box F frequently, if not always, require the participation of two or more separate organizations, each bringing its own specific expertise to the whole enterprise. For example, the R&D organization may assign the task of producing and marketing the new device to a firm specializing in the appropriate area of manufacturing, or it may contract with a number of firms for supplying components that it will assemble itself or have assembled by another agency. The variety of organizational structures appropriate for the reduction of a device or service to public practice is extensive, but one thing remains invariant — the innate responsibility of the R&D agency for the performance of the product in the environment in which it is designed to function. Despite all theories to the contrary, the responsibility of an agency developing a product selected for reduction to public practice does not end until quantitative experimental tests show that the product performs exactly according to specifications in its working environment. To have any meaning at all, these tests must be designed for and applied to the version of the device that comes off the manufacturer's production line and not to carefully selected prototypes.

Thus we see that in addition to capabilities I have already described, the people working in Box F must (a) understand production operations sufficiently well to write realistic specifications that govern all pertinent details that affect the reliability and the quantitative performance of the final product; (b) be able to devise quantitative experimental tests that determine unequivocally whether or not the components and the system itself (product) perform according to specifications in their working environment; and (c) establish and operate a communications network that tells all parties concerned what they are supposed to do (this information being arrived at by consensus) and enables each party to report eventually to the project engineer in charge exactly what has been done.

PEOPLE

Later I shall devote a section of this paper to communications. In the meantime let me say a few words about the flesh, blood and sinews that clothe the skeleton shown in Fig. 1, namely the people. Let me say at once that the men and women working in an R&D organization are not cogs in a machine performing prescribed tasks mechanically *but are intelligent members (components) of a system*. In using this phrase I emphasize that it implies everything I have said in the section labelled "Systems."

Consideration of this statement will bring out the qualities and qualifications that enable a person to be a fully functioning component of this organism. It is clear that the person must be interested, and indeed involved, in the long range objective of the organization, for only then will he or she find real satisfaction in contributing to its achievement. This interest must be supplemented by an inventory of appropriate experience, talents and skills to implement ideas inspired by the objective, and fortified by will power and determination to overcome the many obstacles that beset the path of those who seek new valid knowledge or invent something really new. The individuals composing the organism must have a common background of experience which enables them to communicate with each other, to pass on the information they generate, and to understand promptly the exact significance of information generated by others. As I shall discuss, this entails both the *acquired* and *inherited* mental inventories of the individuals, the common experience and standards they share with their fellows.

The systems approach reminds us that the choice and assignment of responsibilities in this system is one of the most important duties of those who would lead and manage the organism.

In all organizations the acquired mental inventory, or at least part of it, and the acquired manual skill of the individual are given great weight in the decision to hire him. The acquired mental inventory (AMI) resides in a person's memory and comprises everything he has learned from birth, the totality of all that has come into his mind through his five senses, through communication with his physical and social environment, a mixture of wheat and chaff, fact and fantasy, valid knowledge and myth. It includes the permanent results of an individual's formal education at school, college, university, etc. It also includes the permanent residues of a person's informal education by observation, reading, and contacts with contemporaries, much of which builds up a philosophy of life that may vary from honesty, integrity and self-discipline in all things, including work output on the one hand, to an undisciplined selfishness that leads to low standards of work and equates a job to a paycheck on the other hand.

The professional component of a person's AMI is usually labelled in terms of his or her field of special education, for example engineer (aeronautical, mechanical, electrical, etc.), chemist, physicist, physiologist, pathologist, carpenter, machinist, programmer, etc., and in terms of the degrees or other titles indicating the extent of their educational experience, for example Bachelor of Science, Master of Arts, or Doctor of Philosophy, and master mechanic or journeyman carpenter, etc. Due largely to the propaganda of educational institutions, great weight is given to these labels by large R&D organizations, especially government agencies, in the hiring of and the work assignments given to people, despite the fact that these labels are often not really reliable indicators of ability of mind and hand.

The vitality of an R&D organism depends heavily on the diversity of talents among its members. To my mind these talents reside in their "genetic memories," attributes of mind that human beings have inherited. If we look at a cross section of the outputs of research scientists or engineers and, for that matter, of people in all walks of life, we may distinguish six types of mind, all of which have made essential contributions to the progress of science and the achievements of the useful arts, namely: (a) the Promethean or creative, (b) the critical and analytical, (c) the cumulative and inductive, (d) the cumulative and descriptive, (e) the meticulous, and (f) the routine-industrious. The nomenclature is my own and the categories are based on pragmatic rather than on theoretical grounds.

Since this classification still seems to excite some interest, I will enlarge on it by quoting from my original article.[6]

> ". . .The creative mind tries to inject something new into anything it does, it may provide the flash of genius that shows up a new continent of knowledge or gives rise to a new all-embracing theory; it may throw new light on old, tough problems; it may just invent an easier and better way of doing an old job. It is a mind that transmutes ideas from one field of experience to another. (b) The critical and analytical mind takes nothing for granted but examines closely all statements presented to it, probing deeply into their consequences for consistency and rigor. It is the questioning mind so needed for clarification of complex situations and for establishing the validity of experience. (c) The cumulative-inductive mind ranges in the literature and in experiment, collecting facts and attempting to put them in order. It is a type of mind which has contributed largely to physical chemistry. (d) The cumulative and descriptive mind is that of the trained and keen observer who remembers what he sees and describes clearly for others to read. It is the mind which has laid the foundations of the complex sciences of astronomy, geology, and natural history. It is always evident on the frontiers of knowledge and is the stock-in-trade of the effective teacher. (e) The meticulous mind is concerned about the correctness of all details in observation, procedure, and processes. It is concerned with the search for accuracy and precision. (f) Finally, we have the routine-industrious mind that follows through relentlessly, especially where many experiments are needed to establish one fact and where repetitive processes are of the essence.
>
> "History has shown that all these mental attributes have important roles to play in the sound and steady growth of all branches of science and engineering and we should be guilty of intellectual snobbery if we discounted any one of them. The meticulous worker who spends years establishing the real facts in a complex phenomenon or in perfecting a technique, or the routine-industrious man who explores an area thoroughly by a long series of measurements provide means and materials for the inductive thinker and the creative artist, materials they might not be able to get for themselves. The critical mind keeps thought and observation on the track, saving costly detours along the false trails, paying particular attention to the coherence of the inputs and outputs. Each has his place and the secret of the efficient use of manpower either on a laboratory scale or on a nationwide basis lies in assigning to each mind a job suited to its attributes and carrying with it full recognition of contributions to a worthwhile objective.
>
> "I suggest that problems in the distribution and employment of manpower may be approached more realistically on the basis of the mental attributes of scientists and engineers (similar to those I have enumerated) rather than on the basis of their professional training alone. Examples of men transferring successfully their activities from one discipline to another are common, but I believe that, if creative minds are set to work on routine problems, or if routine-industrious minds are given problems that depend on creative ability even in the field of their own training, frustration of the men, mediocrity of product, and a general waste of time are the results."

FUNCTIONS OF MANAGEMENT IN THE R&D ORGANISM[7]

Aside from its better known functions, such as deciding on viable overall objectives, securing financial support, developing material and human resources, allocating resources to leaders of various tasks, and ultimate responsibility for the products, the management has many other roles to play in the R&D organism.

In the experimental and theoretical research areas (Boxes A and C) in Fig. 1, the proper role of management is limited to supplying financial support and resources to very carefully chosen people, giving them wide latitude within a given objective to ask their own intelligent questions and find creative answers. In other words, in Boxes A and C central management should only set a broad objective within which the individual investigators formulate and pursue tactical objectives with complete freedom. An exception to this statement does arise in areas such as nuclear physics and astrophysics where the use of large and very costly accelerators or telescopes by many scientists requires coordination and other aspects of conventional management.

Since the objectives of exploratory development are of necessity more specific, chosen after careful consideration of the usefulness of the results, and involve the efforts of many people, it is obvious that management plays a stronger role in coordinating the operations in Box D. Here again success depends on the freedom given to the workers to ask intelligent questions and find original answers, in other words to set their own tactical objectives — this time, however, with the approval of the "top management," one of whose important duties is to help the workers surmount the difficult and frustrating problems that inevitably arise.

The discussion of Reduction to Public Practice (Box F) given above shows clearly that in this activity strong management is essential. I shall not repeat the discussion here.

The health and the growth of the R&D organism are perhaps the most important concerns of the top management. From a systems point of view, the "feedback" circuits are the indicators of growth or decline and as such provide indispensable information to the manager. The change in the feedback in any loop from positive to negative, or even zero, is a sure sign of trouble such as bad thinking, bad workmanship, indecision, indifference or faulty communication.

The early diagnosis and cure of the underlying troubles becomes a challenge to the alert manager.

COMMUNICATIONS

The concluding paragraph of my 1962 papers[2] reads:

> "All of this part can be epitomized by the statement that the prime function of R&D management is to devise and operate an organization that *makes the most effective use of time.* Time is the most precious commodity we have, the only one in really limited supply, and it is the common basis on which all must compete. The effective use of time requires that combination of thought and action that keeps an organization ahead of its rivals in the quality and quantity of its output. It also demands constant scrutiny to detect and eliminate time-wasting activities. Effective use is made of time when the experience of the past brings deepened knowledge and sounder judgment, when the future is planned in terms of imaginative, yet realistic objectives, and when the present focusses the efforts of growing and enthusiastic individuals on the attainment of these objectives."

Of the various time-wasting activities that may beset the R&D organism, we may mention a few that are not only of concern to management but are within its power to control by constructive action. These are: apathy and boredom arising from fatigue of objectives; shoddy execution, thinking and workmanship; indecision; and misunderstandings of objectives. In this paper, I shall concentrate on misunderstandings and say something about indecision, but the first two items will not be discussed. The reader will find something about them in my earlier paper.

Misunderstanding of Objectives

This is a very common source of time wasting which, curiously, arises from an important organizational asset, namely the practice of the art of delegation. One level of management tells another what is required to develop part of a system, but not in detail how to fulfill this requirement, although it must be aware that the requirement can be met by means short of a technological miracle. The chief source of misunderstanding is inadequate transfer of information from one mind to another. The term "failure of communication" is widely misused, often with the connotation of triviality, an excuse for a mistake. Actually, faulty communications are not to be regarded lightly. The manager at any level who neglects the science and art of communication does so at his peril. Notorious examples abound and include the failure of communications that led to World War I.

Let us look at some of the essentials of human communication in terms of two simple diagrams (Figs. 2 and 3). Although Fig. 2 contains elements

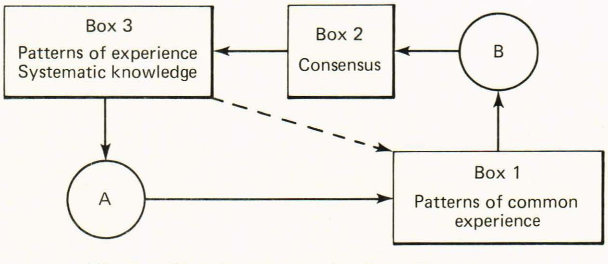

Fig. 2—Simple communication diagram.

common to all communication, its prime object is to illustrate essential elements in scientific communications, of which examples are: the teaching of physics, chemistry, mathematics or any science to students; a paper read by an investigator to an assembly of his fellows; or the communication of scientific concepts by scientists to laymen. It emphasizes that *all* effective communication must involve feedback as well as direct links. The arrows indicate flow of thought between persons (**A**) and (**B**). Box 3 represents the reservoir of established systematic knowledge available to **A**. Box 1 has two functions: it is a reservoir for **B** and also acts as a variable conductor, its conduction of understanding being proportional to its content. If **A** and **B** have little or no experience in common, Box 1 represents a high resistance to the flow of thought. Box 2 (Consensus) is essentially a switch with two positions, ON and OFF. The dotted line represents the transfer of information from Box 3 to Box 1 without the mediation of **A**, for example by intelligent reading.

Let us assume that **A** has a message which he thinks new and important to give to **B**. If **A** is successful the circuit shown is one with positive feedback. Its output, namely **B**'s fund of knowledge rises exponentially. In order for **A** to get his message to **B**, he must first seek an area where he and **B** share experience in common, an area with which **B** has, or thinks he has, some familiarity. Here I am making the assumption that a person understands something new or strange when he can relate it to something with which his experience has made him familiar and not otherwise.

We may consider several cases illustrated by this diagram. In Case 1, Box 1 conducts well, and **B** understands the new knowledge contained in the message and accepts it. The consensus switch is closed, and thought flows freely in the circuit. Some of the contents of Box 3 are now to be found in Box 1, whose conductivity increases, positive feedback occurs and **B**'s knowledge grows exponentially. In Case 2, **B** has not understood the message and honestly cannot accept it. The consensus switch remains open, no thought flows in the circuit, and reiteration is called for if both **A** and **B** are really serious. **A** must redetermine whether Box 1 is really conducting or not and, if not, how he can couch his message in terms more compatible with **B**'s familiar experience. Herein lies part of the art of teaching. We may consider Case 2a which is not too uncommon. **B** has not understood **A**'s message but for reasons not always laudable, wants **A** to believe he has and closes the consensus switch. However, Box 1 is still a poor conductor and **B**'s knowledge does not grow, creating a situation which soon becomes apparent to **A**. There is no real cure for this deplorable situation, I shall refer to it in a later section, Art and Science of Human Communication.

In Case 3, **B** understands **A**'s message but does not accept it and the consensus switch is not closed. This case has points of great interest. First, **A** may not be as good a scholar as he is a teacher, his knowledge and understanding of the content of Box 3 may be faulty, and **B** realizes that there is an inconsistency that he cannot accept in what he has been told. This reason for lack of consensus is not uncommon — its remedy is simple, provided that **A**'s academic pride or embarrassment does not paralyze his intellectual integrity. Second, there may be flaws in Box 3 itself — established patterns of experience may not be consistent with new experience or not be able to stand up under the scrutiny of **B**'s fresh mind. In this case, a real problem exists, a problem which can only be solved by intelligent research to reconcile theory and practice. The probability of the occurrence of this cause of lack of consensus varies greatly with the stability of the patterns of systematic knowledge in the field in question. In classical physics, chemistry and mathematics, this probability is very low, but not zero. In modern physics and chemistry, particularly astrophysics, nuclear physics and biochemistry, this probability is higher, possibly of the order of 40%; it may be slightly higher in biology. In the areas of the social, behavioral and clinical "sciences," the probability of this second aspect of Case 3 arising is still greater, 80% or more, and with such subjects as "management sciences," the probability may exceed 90%.

It should be remarked that growth of systematic knowledge in a given area is promoted and refined by lack of consensus. Indeed, the present stable state of systematic knowledge in physics and chemistry is the result of many controversies involving many minds in the study, the laboratory and the classroom, each of which made a contribution to eliminating error and misconception.[8]

COMMUNICATION IN SYSTEMS ENGINEERING

Let me now extend Fig. 2 to narrow its significance to that part of Fig. 1 which deals with Exploratory Development and Reduction to Public Practice. Figure 3 is Fig. 2 modified by the addition of two typical characters **C** and **D** which form the ends of a hypothetical management chain **C, A, B, D,** each of which has responsibility for the achievement of an objective noted at the top of the figure. To add realism, I have placed $\mathbf{A}_1$, $\mathbf{A}_2$ etc., in the appropriate boxes to indicate that there are generally a number of subsystem, design or component objectives involved in any one system objective.

First, there is the overall objective of the organization, for example, the design and production of a satellite, the design and production of a prototype guided missile, or a fire control system. The function of **C** (supported by an appropriate staff) is to analyze and decide on the overall system objective and have it broken down into subsystems or technical objectives, for example, in the case of a missile, the design and fabrication of a guidance subsystem, of a propulsion system, etc. The red circuit represents **C**'s communications, for example those with **A**, (a group

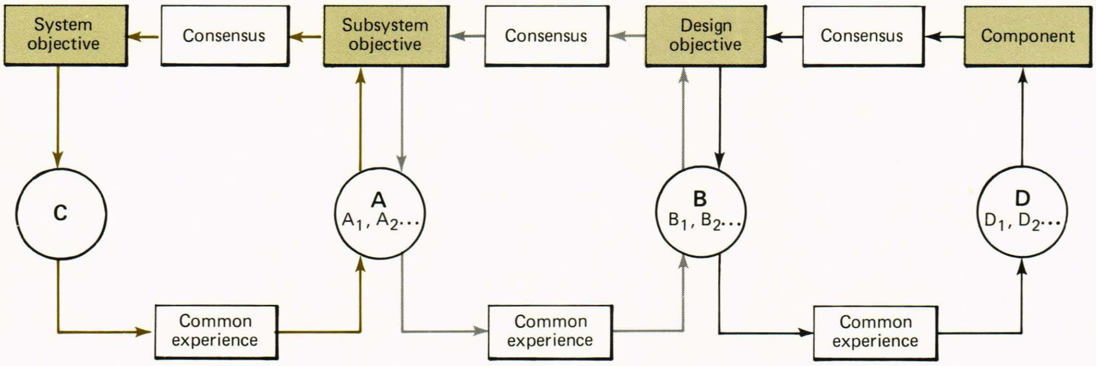

Fig. 3—Communication of system objective.

supervisor perhaps). **C** tells **A** he wants a propulsion system with certain definite characteristics. A goes to work with the help of **B**, $\mathbf{B}_1$ etc., and formulates a specific subsystem objective (or a number of subsystem objectives). Closing of the consensus switch indicates that **A** understands and accepts **C**'s requirement, and that **C** understands **A**'s answer and accepts it. The circuit begins to oscillate and action results. When the subsystem objective is established, **A** communicates the results to **B**, who goes to work with **D** to formulate design objectives, setting forth in some detail the characteristics and the design of components that will satisfy the subsystem objective. The black circuit goes into operation and the result is a consensus of **A** and **B** as to a specific design objective for whose implementation **B** assumes responsibility, communicating the design objective to **D** ($\mathbf{D}_1$, $\mathbf{D}_2$ etc.) who translates it into the detailed design and fabrication of a component. The blue circuit operates. Inherent in this diagram is another set of important feedback loops that are not shown specifically. I refer to the test and evaluation loops which establish experimentally the ability of the components to fulfill the objectives set. These loops begin with **D** and end with **C**. For example, let us consider a ramjet propelled guided missile. **D** is responsible for the development and fabrication of a fuel pump. His test and evaluation program is designed to test all the entities that make up a fuel pump and demonstrate that his product fulfills all the requirements set by **B**, who in turn, being responsible for the design of a combustor, assembles the products of **D**, $\mathbf{D}_1$, $\mathbf{D}_2$ etc., and demonstrates experimentally that all work together to give a combustor whose properties meet the design objective he had undertaken. Similarly **A**, whose subsystem objective is the production of a complete engine, demonstrates that the outputs of **B**, $\mathbf{B}_1$, $\mathbf{B}_2$ work together in an engine that satisfies the subsystem objective agreed upon by **A**. Finally, **C** is responsible for demonstrating that the complete missile fulfills the operational requirements set for his program.

One might imagine an organization with such a perfect communication system that one cycle of the operation I have just sketched would suffice to turn out a reliable finished product, but such would not be worthy of the name "Research and Development Organization." The chief purpose of an R&D organization is to develop and reduce to practice new commodities, tools or services — products that add new choices for action to the customers. All its objectives are therefore set with a certain amount of uncertainty; its operations involve the risk that in trying to achieve its objectives insuperable obstacles may be met. The word insuperable, however, depends not only on the nature of the obstacle itself, or the difficulty of the technical problem to be solved, but very much on the ingenuity, skill and perseverence of the people trying to surmount it. For example, in the early days of the Transit program, the unpredictable refraction of electromagnetic waves passing through the ionosphere presented what some authorities thought to be an "insuperable obstacle" to the achievement of the overall objective, but it was overcome by the ingenious use of two radiations of different frequencies whose different paths through the ionosphere enabled the observer to compute its disturbing effect. The natural obstacle was bypassed.

In an R&D organization, therefore, very fine judgment must be exercised in establishing objectives at all levels, and flexibility must be provided for changes, particularly in the technical (design) objectives. In fact, when the risk attached to a technical objective is considered to be very high, it is wise to plan for the simultaneous exploration of alternate technical approaches to the same problem, the ultimate choice depending on the outcome of both efforts.

Indecision

This brings us to the second time waster, namely indecision, which is really part of the communications problem. In fact, a simple-minded view might suggest that indecision is delay in closing of one or more of the consensus switches in Fig. 3. The first cause may be called "inadequate upward communication." In order to make an intelligent decision about a course of action (closed consensus switch in the red circuit), **C** must have a clear and somewhat detailed idea of what are likely to be the consequences of his decision, and he depends on **A** for this information. A common device for presenting this type of information requires **B** to prepare for **A** two or more choices for action, each supported by a detailed description of its implications, technical risk or feasibility, cost, manpower requirements, time scales, etc.

Another source of indecision is what I might call the "green grass effect." As the reduction to practice (hardware) of a design or technical objective proceeds, the workers (**A**, $\mathbf{A}_1$ ... **D**, $\mathbf{D}_1$ ...) almost invariably run into unexpected difficulties that present annoying problems. Doubts begin to arise concerning the feasibility of the specific technical objective being pursued, and the temptation to look for an easier alternative objective is overwhelming. The engineers look over the fence and see greener pastures in the next field. Perhaps with great ingenuity and skill and a lot of wisdom, a change for the better may result from this type of thinking, but as a general rule, I think we may say that difficult implementation problems arise in the achievement of any technical objective, and these are only found when one gets down to the details. Time is wasted in argument over specific technical objectives, and changes may introduce perturbations that may spread through the whole system. If a new specific objective is decided upon, it may be found that it has as many, if not more, difficult problems as did the original one. The remedy in this type of indecision is dogged perseverence to push a commitment to the conclusion through thick and thin.

ART AND SCIENCE OF HUMAN COMMUNICATION

Like medicine, management and studies of human behavior, and in the past, engineering, physics and chemistry, communication is going through the stage of being an art struggling to become a science. In some disciplines such as physics, chemistry and, in the last few years, biology, the transition from an empirical art to a systematically understood science has progressed a long way — so far, indeed, that we are apt to think of physics, for example, as completely an exact science and forget that intuition and the arts still play an important role in advancing our knowledge of the physical world.

Why have physics and chemistry advanced so far to the status of exact sciences while areas of more immediate concern to us, the social sciences, economics, mob psychology, etc., are still arts, and black ones at that?

Let me hazard an answer to this question. To become an exact science, a body of knowledge must become *public property* in the sense that anyone who is willing to take the trouble can validate or invalidate for himself the facts of which it is composed. Private revelations and mysteries are intolerable. In order to establish this public basis for validation of his results, a scientific investigator must have a language by which he can describe *exactly* what he did and what were his results, a problem in communication in which *consensus* plays a large role.

Fortunately, about 300 years ago, Galileo and his contemporaries found such a means of communication of knowledge from one mind to another. Although we live in a world of colors, sounds, tastes, smells and feelings, and their spatial and temporal relations, Galileo and Company realized that the properties of matter depended on the interactions of matter with an intelligent observer (I use the word in the sense used in the first part of this paper). They sought to find what properties inherent in matter itself produced the effects of color, sound, etc., in the mind of the observer and could be imagined as existing even if no observer were present. He, Descartes, and others came up with a set of "primary properties of matter," particles of different masses, velocities, accelerations, shapes, sizes and vibrations to which later were added electrical charges, etc., which, it turned out, could be weighed and measured with great precision and expressed in numbers and units adaptable to the logic and language of mathematics. The success of this communication system in giving us a mental model that accommodates millions of facts, predicts new ones and makes the whole universe open to our understanding needs no elaboration here.

Up to the present the social sciences lack this vital system of exact communication. Their basic facts are not based on quantitative observations of properties that are independent of the observer. True consensus is almost impossible; *pseudo consensus* is common.

Students have reduced some of the phenomena of communications to a science. We can understand quite well what are the conditions under which one computer can communicate with another. However, communication between human beings is a more complicated matter and I have tried to bring out these complications in Fig. 4. This figure gives my idea of what goes on inside **B** (Fig. 2) when he receives **A**'s message. We should first note that this signal contains a lot of noise — signals that **A** included unintentionally in his communication, the tone and amplitude of his voice, the look on his face, the very language he used to convey meaning. The science of communication has given us insight into information processing and the principles for separating signals from noise, so solutions to these problems may be considered to be in sight.

The train of events pictured in the boxes (Receiver, Decoder, Encoder, and Comparator) is also quite straightforward and bit by bit the neurophysiologists are establishing the details of the processes that go on in these boxes. Indeed, we can justifiably hope to build a computer that can simulate these processes someday soon. Here, however, the science of communication runs into major difficulties arising from (a) the contents of the memories; although all human beings (at least those brought up in the same culture) share much in common in their acquired mental inventories, there are individual differences which, however small, may strongly influence the ouput of the comparator; and (b) the output of the com-

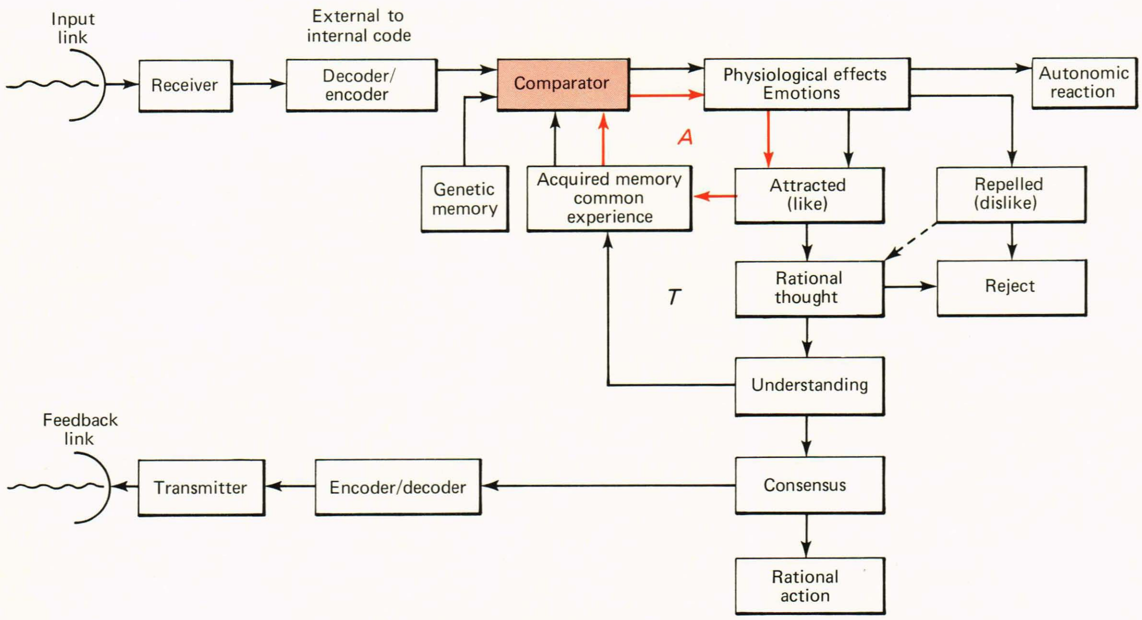

Fig. 4—Hypothetical flow of thought in response to a communication.

parator which feeds directly into the neurophysical system of the individual. It first arouses emotions and only secondarily, if at all, leads to rational thought. I make this suggestion from observation, and on the general principle that the emotions (for example fear, pain, pleasure, love, interest, enthusiasm) are the animal body's first line of defense in the struggle for survival, the primary objective of this sytem.

We recognize that the neurophysiological systems differ from individual to individual and in any given individual their states fluctuate widely about a "normal value" with time and with immediate past history, such as traumatic emotional or physical experiences. The emotions aroused determine to a large extent whether or not the message is accepted. If the recipient likes the message, it may then go through the box labelled Rational Thought, where it is analyzed for consistency through a link (not shown) to the memory, and as a result the recipient understands or does not understand the thoughts communicated to him. If the rational thought processes result in understanding, the information is added to his memory, a consensus is reached which is communicated back to the sender as shown, and appropriate action results.

If the emotional response to the output of the comparator is negative, the recipient may reject the message out of hand, but the disciplined mind may decide to think about it (dotted arrow) and then may reject it or find that it makes sense (understands it), and there follows a feedback of consensus. Indeed, one might say that the extent to which a mind analyzes communications which repel it emotionally immediately upon reception is a measure of the education and discipline of that mind.

The interposition of this box (physiological effects, emotions) emphasizes how complex are the problems of human communication. The reader may argue that this box is really not in series with the chain of events following the receipt of a message. I hope he will, for here a lack of consensus will certainly lead to the elucidation of a very important problem.

There is at least one more feedback loop which is so important that I have outlined it with colored arrows. Its effects are extremely disquieting because they may be both "good" and "bad." I refer to the loop **A** which starts in the emotional reaction to a message and leads directly into the memory without going through the process of rational thought (loop **T**). In other words, people may store in their acquired memories material which has come in through their senses but has never been subject to the scrutiny of their rational thought, and then use the material in the comparator to pass judgment on new information and generate reactions to it.

Loop **A** symbolizes one of man's important assets for survival — very early warning of danger from the external world coupled with instant defense response. On the other hand it fills our memories with unreliable knowledge and actually produces what I may call *pseudo consensus*, that is to say acceptance of messages without understanding their contents. This loop is exploited to the utmost by the advertiser, the rabble-rouser, the rumormonger, the propagandist and all others who purvey unreliable knowledge either from sordid motives of greed or from high-minded, well intentioned motives of attracting people to "good causes." It is the mental loop that induces in people fear of the unknown, the unfamiliar, fears which can generally be dissipated or alleviated if the afflicted individual can force himself to use the "rational thought" channel to analyze the new information before accepting it, that is to say before storing it in his acquired memory.

In *The Meeting of East and West,* the late F. S. C.

Northrop, Professor of Philosophy at Yale University, discusses two components of human knowledge, the *aesthetic or immediately apprehendable component* and the *theoretic component*, emphasizing the relative importance of both in human cultures.[9] I think we can reasonably identify the *aesthetic* component with that which came into people's acquired memories via loop **A** and the *theoretic* component with that which found memory storage after going through the route of rational thought and understanding (loop **T**).

The colors and their variation in time and space that constitute the beauty of a sunset, the color and form and perfume of a flower, the intricately woven and changing patterns of sounds that constitute a symphony, or the simple progression of tones of a haunting melody, all enter our memories through loop **A**. We enjoy them because they are what our memories have led us to expect. Later some people may think about a painting they have admired or a symphony they have heard and attempt to analyze the art of the painter or the composer, but to most people the memory of the beauty (or the ugliness) of the work as it appeared in its completeness through their senses and their emotions is the residue by which they judge later works or phenomena.

The part played by the genetic memory's input to the comparator is very hard to identify except perhaps in extreme cases, for the disentanglement of hereditary traits from those acquired from parents and friends in very early childhood presents a very abstruse problem. I must leave a discussion of this topic to another time or to other people, with the remark that the genetic memory probably influences the output of the comparator to bias the neurophysiological system to the degree to which incoming information is channelled to loop **A** rather than to loop **T** or vice versa. This is just another way of saying scientists and engineers, like poets, are born, not made.

We all recognize that our system of education of the young promotes the development of loop **A** to the detriment of loop **T** in the growing mind, and unfortunately this persists in many centers of higher education. Generally, but fortunately not always, students are expected to accept without question the material presented by the teachers, and he or she with the most retentive memory and the ability to regurgitate its contents in examination papers received the highest awards. The student who thinks about what he or she is taught and cannot always close the consensus switch is frequently regarded as a nuisance. One needs only to analyze, even superficially, the myths that pass for history and the scientific subjects that are taught with a dogmatism only paralleled in theology.

Thomas C. Poulter, an outstanding experimental physicist, explorer and administrator of research, once made the following remark to a meeting of research administrators when the subject of technical education was being discussed: "My father often told me that horses are trained but men are educated." He brought out the subtle difference between two words often misused interchangeable. Loop **A** is the loop whereby people are trained to be cogs in a machine, to obey orders reinforced by rewards and pubishments. Loop **T** is the loop whereby people are educated to become components of a viable system, be it in an R&D organism or any other cooperative human activity.

The education of the people who form the flesh, blood and sinews of the R&D organism strongly affects their background for intelligent communication and hence their effectiveness in the operation of the entire system. Fortunately, we cannot breed and educate from scratch the human components of the R&D organism as we can design and fabricate the components of an electromechanical system. The results might be horrendous. But we can select for the system people who are educated in spite of fashionable educational dogmas. Furthermore, the potential capacity of the human being to adapt to its environment and to learn is almost infinite. Management of the R&D organism, therefore, includes the creation and maintenance of an environment where this potential capacity may be realized and, by informal and formal education, where its members may be stimulated to think intelligently in terms of the experience of the past, the problems of the present and the hopes for the future.

CONCLUDING REMARKS

A system is characterized by a predetermined objective or set of objectives whose achievement is attained by the cooperation of a number of diverse, intelligent components. A research and development organism is a system whose components are themselves very sophisticated systems called human beings, whose performance is largely determined by their past history and present education. The *scientific* design and operation of an R&D system requires a much deeper and more extensive understanding of these components than we now possess. We must, therefore, rely on our indefinable strategic reserves as *artists* — intuition, observation, empathy and painstaking practice — to organize and manage such a system.

In this essay I have suggested some thoughts gleaned from experience with electromechanical and biological systems that may be pertinent in systems composed largely of *Homines sapientes*. These thoughts may be epitomized by three sets of words, the first pertaining to the management in general, the second to the components, the third to their interactions; namely (a) viable objectives, environment, *esprit de corps*, interest and support; (b) talent, education, constructive thought, skillful action, enthusiasm; (c) timely communications, feedback, consensus and growth. In this imperfect world, the ideal organization may never be realized, but I think that the scientist or engineer who ponders the meaning of these words and acts accordingly may achieve a rough approximation of an intelligent answer to the question, What is meant by the phrase, *The Management of Research and Development*?

REFERENCES and NOTES

[1]Based on a lecture delivered to the APL students of the class in Organization Dynamics, March 20, 1980.

[2]R. E. Gibson, "A Systems Approach to Research Management," *Research Management* **V**, pp. 215-228, pp. 423-437 (1962), **VI**, pp. 15-26 (1963).

[3]J. E. Lovelock, *Gaia, A New Look at Life on Earth.* Oxford University Press, p. 146 (1979).

[4]V. Bush, *Science is not Enough,* Morrow, New York, p. 11 (1967).

[5]It should be noted that I am completely ignoring the effects of professional advertising in this discussion. I recognize that in this day and age the management of an R&D organization that does not lay great weight on the power of advertising, especially in the public acceptance of shoddy products, does so at its peril, but in this paper I am speaking about ideal situations uncontaminated by shortsighted policies based on human greed. Indeed, I would ascribe the current admitted decline in the innovativeness and productivity of American industry to three factors: (1) the power of professional advertisers in all media to persuade the public to pay for second, third, or fourth rate products; (2) those schools of management that let loose on the public "managers" whose credentials and labels bear little relationship to their real abilities to carry out the responsibilities they presume to assume; and (3) the interference of well-meaning, but misguided, government officials in the day-to-day conduct of organizations such as I am now describing.

[6]R. E. Gibson, "Enhancing our Potential in Research and Development," *Armed Forces Chem. J.* **7**, 27-32 (1953).

[7]Throughout this essay, I have used the terms "management," "top management," etc., for lack of better words to indicate concisely leadership, control and guidance of the destinies of a system by one man, supported by a group of experienced and wise colleagues. I use the word with some reluctance. Its very origin, the training of horses for the exercise of the manege is dubious. Its use in the press generally is concerned with management-labor disputes where the exploiters are pitted against the exploited. To many it conjures up the notion of persons sitting in plush offices arbitrarily issuing ukases that cold-bloodedly affect the lives of thousands of honest toilers.

I use the term having in mind the analogy with the central nervous system, which provides overall management in the system known as the human body. Most of the body's subsystems function autonomously. For example, the baroreceptors in the arteries sense and regulate blood pressure, sensors determine the oxygen content of the blood and provide information to the lungs, etc., but, when variations exceed the dynamic range of these local control systems, the central nervous system having contact with all the subsystems can make system-wide adjustments that bring matters under control. Furthermore, the brain, as the focus of the body's management system, stores and rearranges the information coming through the senses to produce new thoughts, plans, etc., that enable the system to adapt to and make the best use of its environment, always having in mind the system's ultimate objective, survival in a hostile world.

Like the central nervous system, the management is a part of, and must grow with, the organism itself, and even perish with it. I would not like to travel on a ship whose captain had not come up through the ranks of the seafaring profession but got his training in "seafaring management." He might do a good public relations job in fair weather but what would he do in foul weather or in an emergency when prompt action based on long experience is called for? I think these considerations apply to the management of any kind of system.

[8]An excellent discussion of "consensus" and its importance in the development of scientific knowledge is given by John Ziman, *Reliable Knowledge*, Cambridge University Press (1978).

[9]F. S. C. Northrop, *The Meeting of East and West, An Inquiry Concerning World Understanding,* The MacMillan Company, New York, pp. 300 ff (1966).