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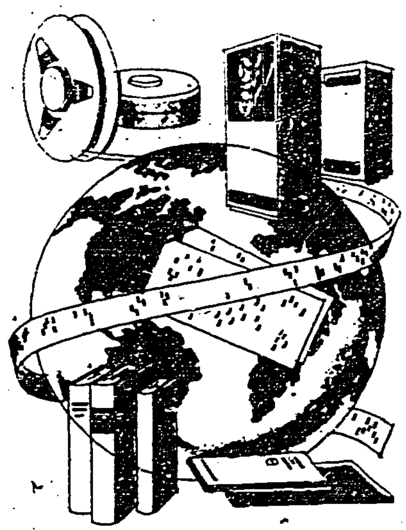
ABSTRACT

This volume contains the reports of three working groups which were convened separately over a 3-year period at the request of the Advisory Committee for the Division of Information Science and Technology of the National Science Foundation to obtain the opinion of experts concerning research opportunities and trends in information science and technology. Each group was charged with identifying research questions in information and technology that lie outside the more established disciplines, but could contribute to the understanding of fundamental questions that might foster the development of new knowledge. Taken together the three reports provide an overview of information science and technology which shows its relationship to its neighboring disciplines while also clarifying the essential ingredients that distinguish its thematic scientific problems from theirs. The first report suggests that fundamental questions relating the phenomena of learning and memory in animals to a theory of "cognitive processes" may create future bridges to the fields of automata theory and artificial intelligence. The second report confirms that the technology that has raised many questions because of its rapid and pervasive development is itself in need of more intense basic research in eight general areas, each of which is discussed in turn. The third report recognizes that economists are only beginning to develop theory with respect to the cost and distribution of information viewed as a commodity. (DMC)



Research Opportunities in Information Science and Technology:

- Cognitive Aspects of Information Science
- Information Technology
- Economics of Information

Division of
Information Science and Technology

Directorate for
Biological, Behavioral, and Social Sciences

National Science Foundation

1982

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PREFACE

In order to assist it in fulfilling its oversight and advisory responsibilities, the Advisory Committee for the Division of Information Science and Technology of the National Science Foundation has periodically sought the opinion of experts concerning the research opportunities and trends in information science and technology. This advice is particularly important for the Division of Information Science and Technology, because it is new in the Foundation and because much of its research agenda is formulated from the intersection of other disciplines. This volume contains the reports of three special Working Groups which were convened separately over a three year period at the request of the Advisory Committee for that purpose. Each Working Group was chaired by a member or members of the Advisory Committee. Each Group was charged to identify research questions in information science and technology, if any existed, that lay outside the more established disciplines but that could contribute to the understanding of fundamental questions that might foster the development of new knowledge.

Information science is a relatively new discipline which has natural points of contact with other disciplines such as the cognitive sciences, computer science, and those parts of the social sciences that are concerned with the organized, quantifiable, and goal-directed behavior of collections of individuals. As a consequence, information science and the associated technology have strong interdisciplinary ties to these fields. Taken together, the three Working Group reports provide a responsible and broad-gauged overview of information science and technology which shows its relationship to its neighboring disciplines while also clarifying the essential ingredients which distinguish its thematic scientific problems from theirs.

In all respects these reports represent an auspicious beginning—a foundation on which can be built research of lasting value in a society increasingly influenced by the effects of information technology. Each of the reports suggests a research agenda that is rich in content and diversity, and that in most cases can be conceptually translated between the abstract and the real with only modest imagination. For example, one report suggests that fundamental questions relating the phenomena of learning and memory in animals to a theory of "cognitive processes" may infer future bridges to the fields of automata theory and artificial intelligence. Another report recognizes that economists are only beginning to develop theory with respect to the cost and distribution of information viewed as a commodity in a variety of organizational structures—a problem of perplexing dimensions in the social, political, and economic order of the world. The third report confirms that the technology that has raised many fundamental questions by virtue of its rapid and pervasive development is itself a product of research inquiry found in need of more intense basic research in eight general areas. Each of the reports is informative and suggestive in its treatment of the research purview of interest. Each is written in a style that communicates to layperson and expert in different ways, but importantly and effectively to both.

Each Working Group adopted its own procedure for considering its charge and preparing its report. Each Group met at least once in plenary session. The Information Science and Economics Working Group chaired by Leonid Hurwicz held several meetings and conducted a workshop at Northwestern University. The Working Group on Information Technology co-chaired by Paul Strassmann and Richard Tanaka convened its members at the National Academy of Sciences and subsequently conducted small group meetings as its report was prepared. The Working Group on Behavioral and Linguistic Research Bearing on Information Science co-chaired by Duncan Luce and Joan Bresnan held several meetings in Cambridge, Massachusetts and Washington, D.C. as its report was honed to completion.

The participants in each of the Working Groups represented a broad cross-section of distinguished researchers and research directors from business, government, and education. The reports of all three Groups were widely read in draft form and have the benefit of considerable advice from a broad constituency of interest. It is already clear from the research activity in information science and its related disciplines, that the intellectual exchange fostered by the Working Groups has begun to bear fruit.

The opinions expressed in this volume are those of the authors: they should not be viewed as a representation of the field which has been given the formal endorsement of its members, nor as representing the policy or position of the Advisory Committee or the National Science Foundation. But the stature and experience of the members of the Working Groups, and the thoughtful and stimulating content of the reports themselves offer assurance that this volume will offer much of value to the reader whose interests lie in science policy, while the unified view it presents of information science and its research opportunities will act as a stimulant to members of the scientific community.

The memberships of the Working Groups are listed on the following pages. The Advisory Committee has asked me to express its appreciation to each of them for their valuable contribution to which I wish to add my personal gratitude for their willingness to assist the Advisory Committee. Finally, it is my pleasure to acknowledge the splendid work of the Committee members which chaired the Working Groups and to express our joint gratitude to Howard Resnikoff, the first Director of the Division of Information Science and Technology, for the able leadership and imagination which has benefited all of us.

Joe B. Wyatt
Chairman, Advisory Committee for Information Science and Technology

WORKING GROUP ON BEHAVIORAL AND LINGUISTIC RESEARCH BEARING ON INFORMATION SCIENCE

ADVISORY COMMITTEE FOR INFORMATION SCIENCE AND TECHNOLOGY

NATIONAL SCIENCE FOUNDATION

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NATIONAL SCIENCE FOUNDATION
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Report of the

WORKING GROUP ON BEHAVIORAL AND LINGUISTIC RESEARCH BEARING ON INFORMATION SCIENCE

of the Advisory Committee for Information Science and Technology National Science Foundation

Abstract

A variety of problems involving the transfer, storage, and retrieval of information have, so far, eluded solution within the framework of current science and technology and yet are readily solved by biological systems. Some seem highly specific to humans, e.g., chess playing and language; others are found widely dispersed among animals, e.g., recognition of complex stimuli, categorizing, and learning. This report reviews some of the main lines of research in the behavioral and linguistic sciences that appear to shed some light on the biological solutions to problems of the abstraction, storage, retrieval, and use of information. Although the specific examples may be somewhat idiosyncratic, the broad outline of the several topics is less so.

Although much current concern with information—its communication, transmission, abstraction, storage, retrieval, and use—arises in connection with physical systems, especially those drawing upon computer and telecommunications technology, the most challenging information handling systems are still biological. They exhibit features of great importance that are not yet well mimicked by artificial systems—e.g., extraction [illegible] from text materials, identification of [illegible] in complex environments, [illegible] coping with imprecise directions or discussion, associative memory, and the like.

Because biological systems often appear to be more subtle and flexible, although less systematic, fast, and patient, than contemporary artificial systems, it is of much interest to understand the principles of information processing that are used. Is our ability to recognize all sorts of handwriting and type fonts wholly a matter of programming complexity and cleverness or are there principles involved we do not yet understand? Once the biological strategies are discovered, what impact will they have on information technology? It is easy to suggest an analogy to powered flight—although we understand something of how birds power their flight, it is unlikely that these techniques will ever compete with jet engines. Yet, perhaps, there are biological principles of information processing and storage quite different from any that have been thought of. If so, then when these principles are elucidated and cast in abstract form they will have important hardware and/or software implications.

One important aspect of human functioning, which is possibly related to limitations in the brain, is that many of the brain's special purpose devices appear to be able to perform certain tasks well only at the expense of doing others badly. For example, there is a certain amount of evidence that children with dyslexia are remarkably good at certain kinds of visual-spatial tasks and that many of them draw very well.[2] This may be related to the fact that artificial devices and human beings often differ in what they do best: chess-playing computers play in a style different from humans, in part because they can, in fact, do certain things that the human being cannot do, such as make more calculations of the effects of possible moves. However, the computers seem, as yet, not to respond to or to evaluate more global aspects of positions on the chess board, a human ability perhaps akin to the identification of natural categories discussed below.

What follows is one possible outline of studies directed at the several aspects of information processing in biological systems. The examples are illustrative, not exhaustive, and to some extent reflect the backgrounds of the authors.[1] The topics fall under two major headings: *[illegible] representation of information*, and *principles [illegible]mentation*. The representation problem subdivides [illegible] questions about the nature of the representations, their storage and retrieval, their control of behavior, and their communication.

THE REPRESENTATIONS OF INFORMATION

Nature of the Sensory Code

One striking finding of peripheral neural physiology and psychophysics is the complex, scrambling nature of the sensory transduction. It is nonlinear with a vengeance, transforming what amount to continuous inputs into stochastic processes—neural pulse trains. And once the transduction is completed, the recoded information tends to spread into various neural circuits of increasing complexity. Two things seem to be clear. First, not all of the transduced information is attended to by the higher processing centers. Second, there appear to be built-in structures that make the organism sensitive to unique configurations of stimulation. As an example, chimpanzees born and raised in captivity are frightened by certain stimuli, such as snakes or dismembered bodies, with which they are unfamiliar.[3] Such work can and should be approached on both a physiological and a behavioral level. The latter is essential: the neural wiring is far too complex for us to have any hope of understanding it without rather precise information about the behavioral capabilities resulting therefrom. We take up these two topics separately: attention and natural categories.

Information Overload and Attention

It is evident that far, far more information impinges on an organism than gets transduced, and far, far more is transduced than is used or stored. How do we and other organisms filter, attend to and selectively store information? What are the strategies that permit rejection of much of the information flow at the expense of minimal cost in errors? What are the developmental aspects of this, both in youth and in aging? One senses that at both the beginning and at the end of life biological systems are less able to deal with multiple sources providing high rates of information than when they are fully mature but not yet old.

A great deal of the work currently classed as "cognitive psychology" is concerned in one way or another with the concept of attention.[4] Attempts are being made to understand shifts of attention both among and within modalities. Even in sensory psychophysics the concept has begun to play a role in accounting for the well known discrepancies in performance when wide and narrow ranges of stimuli are employed.[5] And in vision, behavioral evidence has recently been provided that the locus of attention is separable from where one is looking.[6] Moreover, it is possible electrophysiologically, using microelectrodes in the inferior parietal lobule, to separate the locus of attention from where an animal is looking.[7]

Natural Categories—Psychological Approaches

Given that some selection process must be occurring—both actively and passively—how are the choices of categories made? Clearly, the remarkable prevalence of categorization, appearing at so many levels in the animal kingdom, suggests that it must be the source of important economies in the functioning of the brain.

In one animal example, highly taxing to current models of perception, pigeons have been reinforced for pecking a switch in the presence of a photographic silhouette of a particular white-oak leaf and for not pecking in the presence of silhouettes of leaves from other trees, e.g., maple, tulip, elm. From this training, the pigeon generalizes readily to leaves it has never seen, pecking in the presence of white-oak leaves and not in the presence of non-white-oak leaves. The variety of white-oak leaves is considerable, including variation in the number, depth, and placement of its lobes. Yet there is, to the human observer, a typical form for white-oak leaves, and pigeons evidently abstract this form invariance from a single exemplar in comparison with the leaves of other trees.[8]

As an example of what must happen when a person perceives a natural category, consider speech. To perceive a phonetic category—for example, the p that is present in *split* and absent in *slit*—the listener must integrate into a unitary percept a considerable number of acoustic cues, although these are diverse, widely spread through the signal, and overlapped with cues to other categories in the phonetic string.[9] Yet listeners do integrate, and so recover the categories. Research has shown what this process requires of a listener, and it has uncovered much of the acoustic information he uses for the purpose. But it has not yet provided much insight into the underlying mechanisms; hence, we do not know how to design their equivalents for speech-recognizing machines. Speech recognizers are being produced, but they do not always extract phonetic categories as such. Rather, they represent words as temporally complex indivisible patterns of sound, and, perhaps for that reason, deal only with limited vocabularies. They demonstrate little ability to abstract the common linguistic features when the same word arises in different contexts or is spoken by different people. That we human beings are not so limited may be owing to our ability to recover phonetic categories. It is, after all, precisely those categories that the speaker encodes in the speech signal. Accordingly, they are the true units of the message, capturing exactly the systematic phonetic changes that relate the various tokens of a word to its underlying type and also, by marking syntactic and morphological boundaries, provide information important to processing a sentence.[10] It seems important, therefore, to make these phonetic categories available to speech-recognizing machines, but to do so will likely require a better understanding of how human beings perceive them.

Color naming provides another impressive example of natural categories in human beings. It is also a very good example of cross-disciplinary research, involving laboratory psychophysical studies, neurophysiological studies in infrahuman primates and anthropological studies across cultures.

The problem of color naming was initially approached from a cultural relativism viewpoint. We know that the range of visible color hues from red to blue and of color brightness from black to white is continuous. It is possible, in principle, for cultures to divide and label the color continuum as they see fit. To demonstrate the thesis that psychological differences are associated with terminological conventions, early experiments tested the color memory of English speakers. Colors without simple names were both difficult to name or describe and difficult to remember.[11] Such results were initially interpreted to mean that language does constrain thought, but that interpretation proved to be inverted. Subsequent studies demonstrated that particular colors are not distinctive because a culture has given them names. Rather, colors are given names because they are distinctive.[12]

The evidence comes from several sources. Psychophysical studies[13] revealed that certain 8 to 11 primary colors—including those which English speakers call red, green, yellow, blue, black, and white—have special status in color discrimination tests. Neurophysiological research[14] (primarily on Rhesus, which appears to have color-vision identical to human) demonstrated that the visual system organizes these primaries into opponent pairs—red/green, yellow/blue, and black/white. In other words, the organization of color into primary pairs is an innately given biological property of all humans with normal vision; some infrahuman primates, and perhaps lower species. Furthermore, anthropological studies[15] of peoples whose languages contain fewer color terms than English revealed that, in all cases, the "best instances" of the colors named are close to the psychologically primary colors; that these color terms are directly translatable to English. Finally, when memory tests were conducted on people who spoke a language with only two basic color terms, they remembered primary colors best, even though they had no names for them.[16] Clearly, some aspects of color naming are culturally determined: the number of terms does vary. However, the use made of available color terminology is constrained by innate properties of the brain and their relation to information processing, rather than color naming being a matter of pure convention.

Categorization by both subhumans and humans suggests that there is a widely dispersed biological solution to the problem of extracting invariances from variable exemplars, a kind of universal pattern classification algorithm. The presence of the solution in such organisms as pigeons further suggests that it requires relatively little cognitive capacity. It seems likely that natural selection has fostered the evolution of perceptual systems that are predisposed to form categories for the classes of objects that are important to survival. The more subtle, abstract, and dispersed these predispositions are, the more profound is the scientific challenge in finding evolution's solution to the problem of extracting invariances.

This work may well be getting close to the point where mathematical descriptions of conceptual representations would be a true contribution to a science of information representation. The trick seems to be to understand the classes of transformation that leave the category invariant. A deep understanding of the nature of categorical perception should help us to design devices capable of pattern recognition.

Natural Categories—Physiological Approaches

We must consider the possibility that at least some natural categories are, in part, pre-programed or even hard wired into the system. Consider, as an example, the recognition of faces. The belief that this skill may be preprogramed arises from the fact that people with severe disorders in the ability to recognize faces have sustained brain damage (to essentially symmetrical regions on both sides) which is remarkably stereotyped from case to case. Although these patients have gross difficulty in recognizing or learning new faces, they can read, recognize colors, and deal correctly with other visual stimuli, a pattern which suggests there is a special system for the learning of faces.[17]

More generally, the study of animal brains physiologically and of accidentally lesioned human brains suggests there are a remarkable number of such highly specialized devices. For example, a large proportion of laboratory-raised cats who have never seen a mouse attacked will attack, just as animals raised outside do, by biting the nape of the neck. If cats that do not attack spontaneously are stimulated in the lateral hypothalamus, they also bite around the head or neck.[18]

There are few areas other than the study of natural categories in animals where one can so readily cross the boundary between the cognitive sciences and neurophysiology. Of course, true experimental study on the language areas of the human brain may never be carried out, and it is unclear the extent to which work with higher apes will illuminate the problem even if they exhibit forerunners of language, as some investigators have claimed. On the other hand, natural categories may constitute a forerunner of at least one aspect of language, naming. Attaching a distinct response to a class of stimuli is the ingredient common to naming by human beings and categorization by subhuman animals.

STORAGE AND RETRIEVAL OF REPRESENTATIONS

Storage

Although there is some dispute, many workers continue to feel the distinction between long- and short-term storage is useful, a distinction which is in some respects comparable to that between "cache memory" and "main memory" in contemporary large computers. To a considerable degree, much of the physiological work on memory has been devoted to long-term storage, whereas the psychological work focuses both on long- and short-term memory.

The work on short-term storage is a blend of empirical and mathematical modeling. The dominant approach has been to assume that short-term storage is in some relatively small number of bins—roughly seven—which can temporarily store materials of varying complexity provided they are properly packaged.[19] The nature of this store—how it is accessed and at what rate, how it is maintained, how it is transferred into more permanent form—has been the subject of many experiments and theories.[20]

Current psychological, as distinguished from physiological work on long-term storage has focused on the coding of meaningful information such as that contained in sentences. It has been known for some time that less than a minute after a sentence is presented, one has virtually no memory for the specific words actually presented; only the meaning is preserved.[21] This has led to the development of formal and quasi-formal languages for representing meaning in memory, with the idea that variations in memory performance can be better understood in terms of variations in meaning representations than in terms of the actual input. Thus the probability of successfully coding a sentence depends more on the number of distinct meanings or propositions in the sentence than on the number of words in the sentence.[22] Further research along these lines may have important implications for the design of higher level programming languages.

Physiological studies suggest that the persistence of stimulus aftereffects occurs differentially in different regions of the nervous system. In primary sensory pathways the persistence of the neuronal response to a brief stimulus is of the order of iconic memory, whereas in certain neocortical regions and limbic structures the neuronal aftereffects may have durations of the order of primary memory.[23]

Insofar as localization of memory processes is concerned, there is evidence that the visual icon may be stored in significant part in the retina and the visual pathways.[24] Data are much less clear as yet concerning possible anatomical-physiological substrates for primary and secondary memory. Structures of the limbic system, particularly hippocampus and amygdala seem critically involved in the processes of longer term storage and/or retrieval of information in both human and infrahuman mammals.[25] Some phenomena of behavioral plasticity resembling simple conditioned response learning can be induced at reflex and even spinal levels.[26] However, cerebral systems—the neocortex and limbic structures—appear to be necessary for the preservation of the normal parametric features of conditioning and for more complex aspects of learning and memory processes.[27]

In biological terms, analysis of the physical-chemical substrates of memory is in its infancy, in that we are only beginning to gain some idea of the brain systems involved. A clearer characterization and localization of these systems and their interactions in the context of information processing is a necessary aspect of the search for the "engram". Mathematical models having at least some of the characteristics of long-term storage and retrieval are now appearing.[28]

Retrieval

Much of the work on retrieval has been concerned with demonstrating that memory failures frequently arise at the retrieval end of the system. Seemingly forgotten information can often be retrieved by reinstating the context in which the information was learned, indicating that context is a particularly effective retrieval cue.[29] Other studies have focused on factors that diminish the effectiveness of a retrieval cue, like multiple connections to the cue.[30]

There is no guarantee that the processes—algorithms and heuristics—that people use with small data bases are of any use with large ones. Sequential searches, for example, make sense with small data bases but are unrealistic for large ones. For these reasons, research on human retrieval from large data bases seems highly relevant to information science.

Learning

Studies in animal learning have recently come to emphasize processes analogous to those of human memory. The term "cognitive processes" is increasingly being used to characterize this general information processing approach to the phenomena of learning and memory in animals.[31] One distinction is between working memory—stimulus information useful for one trial only—and reference memory—information useful for many trials—in analyzing operant learning in the pigeon.[32] (It appears that hippocampal damage selectively impairs working memory in many species.[33]) Others have analyzed classical conditioning (using rabbit eyeblink) in terms of effects of expectancy and "priming" on short-term memory and have developed hypothetical structures for short-term and long-term memory processes in animal learning.[34]

A learning experience is fragile and easily manipulated for a short time after the experience—it can be impaired by electro-convulsive shock and anesthetics and facilitated by certain drugs, hormones and peptides in both humans and animals.[35] On the other hand, the formation of long-term memory in animals can be impaired by substances that interfere with protein synthesis.[36] These consolidation phenomena provide further evidence for a fundamental distinction between shorter and longer term memory processes in animals as well as in humans.

REPRESENTATIONAL CONTROL OF BEHAVIOR

Decision Making and Heuristics

This area is vast and has attracted a great deal of attention by scientists from various fields. Some of the key words are: subjective probability, expected utility, risk, heuristics, information processing strategies, Bayes' theorem, representativeness, etc. There is a long standing tension between optimal approaches, as exemplified by work often called decision analysis, which is based largely on subjective expected utility theory and Bayes' theorem, and empirical results that show not only that many people (including those with decision responsibilities of importance) fail to behave optimally, but that they do not always want to follow the dictates of optimal models. For example, many subjects will order certain pairs of gambles opposite to the amounts they say are equivalent to the gambles individually.[37] The failure to behave optimally could be due to an inability to handle the information processing required, which could perhaps be compensated by artificial devices, but the failure to want to be optimal suggests some basic misunderstanding either by most people or by the scientists analyzing these decision situations.

It is now generally conceded that human subjects, unless especially trained, approach complex decision problems involving chance events by invoking various forms of heuristics inconsistent with either rational considerations or statistical theory.[38] As yet, no very satisfactory descriptive model has evolved.

Motor Control

The study of coordinated movement has been much neglected, certainly by comparison with perception. Yet the problems of movement are just as relevant to information science as those of perception—indeed, the two are mirror images. In movement, as in perception, there is the problem of many-to-one: how does a movement system achieve a particular objective in so many different ways, from so many different starting positions, and under so many different conditions? From the standpoint of purposive control, how can the degrees of freedom in the system be minimized, or even made manageable? What principles determine, in a given activity, which variables are altered and which are held constant? What are the constraints on the system that restrict its operation to activities that are behaviorally useful? How do we solve the fascinating, but not much thought about, problem concerning the relationship between afferent and efferent patterns? Consider, for example, how it might be that the afferent patterns corresponding to the auditory (or phonetic) representation of incoming speech sounds are "translated" into the efferent patterns that produce mimicry. Note that the process appears to be accomplished with very little trial and error and, in the adult, with such speed as to imply a mechanism that is both efficient and, like so many systems that work efficiently in animals, biologically based. What are the implications of the fact that there appears to be no obvious invariant relationship between central commands and the effects they produce, that the order to pick up an object has wholly different consequences depending on the initial relation between the person's body and the object? This is, of course, the problem of context-conditioned variability, and it looms as large in movement as it does in perception.

To solve these problems will require, at the least, that we discover how to characterize the significant informational units of coordination and the representational structure of objects imbedded in physical space. The attempt to do the former has been a point of departure for work at the Institute for Biological Physics and the Institute for Problems of Information Transmission in the Soviet Union.[39] At those centers, investigations range from studies of the neurophysiology of motor systems, including such disorders of motor activity in humans as Parkinsonism, to the application of ideas about motor organization in the design of robots. The theoretical perspective developed in the Soviet Union has been elaborated in this country[40] and is now being used as the basis for empirical work in several American laboratories.[41] But in seeking to understand the planning and organization of movement, and how perceptual information regulates activity, an integrated research effort is needed. Such an effort will comprise aspects of psychology, neuroscience, and computer science. There are preliminary signs that such an integration is being attempted, but much remains to be done.[42]

Strategies Governing Performance

It would seem likely that a performance strategy which is optimal for some purposes is not optimal for others. For example, in children who have accidentally lost the cortex of one hemisphere, different linguistic strategies emerge in dealing with certain grammatical constructions depending on which hemisphere was removed.[43] More recently it has been reported that with normal aging the strategies used in dealing with certain tasks change, e.g., the ways in which simple drawings are copied.[44] A question raised by these studies is whether such strategies are defective in the sense that the subjects could be trained to other strategies that would give a better performance or whether the strategies are indeed optimal when all constraints on performance are taken into account.

COMMUNICATING REPRESENTATIONS

Connections Between Phonetic Structure and Sound

As a result of years of research, we have begun to understand the nature of the code that connects the sounds of speech to the phonetic message they convey. It is a peculiarly linguistic code, bearing resemblances of a sort to the grammatical codes (e.g. syntax) that one finds at other levels of the system. More specifically, we know the code well enough to have captured it in a set of rules—a grammar, as it were—so explicit that it can be put into a computer and used for the purpose of generating speech from strings of discrete phonetic symbols.[45] The synthesized speech is not wholly satisfactory, but it is good enough to stand as evidence that this part of the problem is on its way to being solved. The rules for synthesis, when examined, suggest that the solution is not trivial. As for the technological side, synthesis-by-rule can be used—indeed, it is now being used—in a variety of applications. When connected, for example, to another set of rules, largely phonologic, that relate orthography to phonetic structures, and to an optical character reader for "perceiving" the orthography, the result may be a reading machine for the blind—that is, a machine that will convert text to speech. Synthesis-by-rule used in conjunction with other devices provides a variety of systems designed to make man-machine interactions easier and cheaper.

Higher Levels of Linguistic Representation

Linguistic comprehension and production involve the formation of multiple representations of the linguistic signal, each of which encodes some aspect of the total information conveyed by the signal. For more than twenty years, intensive research in linguistic theory has been devoted to the formal characterization of these representations and the abstract specification of the mappings among them. The phonetic representation of speech is connected to the lexical representation, consisting of a sequence of words, by means of phonological rules. Syntactic rules connect the lexical sequence to a representation of meaningful grammatical relations. Semantics and pragmatics specify mappings between this representation and a still more abstract representation of the message encoded in the linguistic signal. In computational models of linguistic comprehension and production, the linguistic rules for mapping between representations can be regarded as stored knowledge structures that are applied to decode or encode the information in the linguistic signal.

Linguistic theory has predominately been concerned with formal characterizations of the mental representations that underlie speech, and relatively little effort has been devoted to studying realistic algorithms by which these representations can be computed. Recently it has been argued that new types of syntactic representation based on the lexical encoding of grammatical relations would permit psychologically more realistic processing algorithms.[46] This and the development of advanced natural language parsing techniques[47] makes it appear feasible to construct realistic computational models of human language processing which incorporate linguistically motivated rules and representations. Collaborative work combining linguistic, computational and psychological approaches to this problem has been initiated by groups of researchers in cognitive science at a number of academic and industrial centers.

An important issue for information science arises from work of this type. A major focus of research in linguistic theory has been the discovery and characterization of constraints on grammatical structure that are invariant across languages from unrelated language-families. Referred to as "linguistic universals", these invariants are thought by many linguists to reflect specific properties of human cognitive mechanisms for language-use. Linguistic universals provide a rich source of natural constraints on the design of computational and mathematical models of natural language processing, but one that is just beginning to be exploited in the cognitive sciences.[48] A question for research in information science is what principles of information processing would explain the existence of these universal invariants in the higher levels of linguistic representation.

Understanding

There are a number of projects around the country where researchers are trying to devise computer programs that understand simple and not-so-simple stories, and where the guiding concern is the psychological reality of the representations and processes posited.[49] This work clearly constitutes an information processing account that is independent of its specific implementation, as it deals with a program that is intended to be the functional equivalent of what people do when they understand stories.

PRINCIPLES OF IMPLEMENTATION

Solutions to problems of computing and manipulating representations can be found in at least two ways: (1) by an abstract, mathematical treatment, or (2) by an empirical example. In the latter case, the nature of the illustration will depend upon the machinery available—neurons or chips, optics or computers. For example, if one wishes to represent a complex waveform as the sum of sine waves of differing frequencies, this can be done in a parallel manner using optics, or serially on a computer using a Fast Fourier Transform. Both methods give an equally informative representation of the original waveform. However, the two methods differ considerably in the algorithm used to implement the computation. Clearly, depending upon the form of the input data and the available hardware, one method will be more efficient than the other. An important example is the speech synthesis mentioned above.

With the explosive development of computer technology over the past decade, our understanding of serial processors has grown tremendously. In contrast, relatively little is known about parallel processors, such as animal and human brains. Yet these biological systems can be the most efficient information handling devices available. Understanding the computational "tricks" and strategies of the brain should provide useful insights for the construction of the artificial parallel processors of the future. Perhaps the surest way to proceed in such a "blind" search is to seek and identify general principles that appear almost universally in all biological information processing systems. These principles are revealed on at least two levels: behavioral and anatomical.

The "Magical Number Seven" is an example of a behavioral principle.[19] The average person can recall correctly a list of seven binary digits or seven decimal digits, or seven words, each chosen at random. Clearly it is the total number of items in the sequence that is the limiting factor in the span of immediate memory. This limitation has suggested that the brain will tend to encode material in such a manner that it need not handle more than seven items or "chunks" at a time. The theoretical reason for this empirical result is not known, and yet it suggests an important design principle for storage and retrieval in a hierarchically organized parallel processing system.

Two other design principles that appear both at a behavioral and an anatomical level are "lateral inhibition" and "opponent-processing". One function of lateral inhibition in neural nets is to reduce redundancy. The second is the normalization of the sensory signals over a wide input range. The scheme used to accomplish these tasks has been studied in great detail,[50] and the basic (two-dimensional) Laplacian operator is now used almost universally in image processing. "Opponent-Processing" is a related technique also very common in biological systems. It is the pairing of mutually exclusive signal types, such as "red" opposed to "green" or "black" opposed to "white". Although *why* particular pairs are chosen is not always understood, the universality of this opponent-process suggests that it may be an efficient method for handling information. Its utility can perhaps best be understood as a binary selection strategy, where inputs at each higher level of processing are successively graded by placing the results into one of two bins.

At an anatomical level, we also see the continued recurrence of certain features, which suggest underlying principles of implementation. For example, many structures of the brain are subdivided into layers (laminae) in one dimension and "slabs" or "columns" in an orthogonal direction.[51] Clearly the design of the brain cannot be random, and this type of architecture seems to be one of its organizing principles. The theory of why such a scheme is used has not yet appeared, however, and may await further developments in complexity or network theory. Other organizing strategies used by the brain include reciprocal feedback between hierarchical structures (i.e., cortico-thalamic) or laminae (as in the spinal cord), as well as temporal patterns of interaction that seem to be regulated principally by the limbic system. The latter have been likened to ring memories.

Understanding the design of the brain therefore includes not only the understanding of the problems it faces, but also the manner in which it computes solutions to these problems. By discovering the "tricks" used in common by biological systems, we advance our general understanding of how efficient, parallel information-processors could be built.

CONCLUDING REMARKS

Both the science of information and that of behavior are fast changing fields, each impacting the development of the other. It is not surprising, therefore, that what we have said about biological solutions to information handling is far from comprehensive, and we would be foolhardy to think that our sense of important topics is much of a prognosis as to what is happening right now, let alone five or ten years from now. Our purpose in trying to present the behavioral approach is to foster further interaction, not to prescribe its direction.

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Report of the

WORKING GROUP ON INFORMATION TECHNOLOGY

of the Advisory Committee for Information Science and Technology National Science Foundation

Introduction to the Report

The Working Group on Information Technology was convened at the request of the Advisory Committee for Information Science and Technology of the National Science Foundation under the direction of Advisory Committee members Paul A. Strassmann and Richard I. Tanaka.

The Working Group was charged with identifying research gaps related to information technology which are unlikely to be filled by the private sector but which are important to the national interest and therefore appropriate candidates for Federal action.

Similar questions have been considered by other groups and at greater length during the past several years but generally within the more limited context of particular agency or national interest problems (cf., e.g., [1, 2, 3, 6, 10, 14]). Other nations have generally adopted a more comprehensive and unified position in their consideration of analogous issues (e.g. [7, 9]). It was not the task of this Working Group to reiterate the arguments of previous studies nor to undertake a detailed study itself, but rather to synthesize prevailing knowledge and expert opinion at the most comprehensive level in terms of both subject matter and its potential significance for the nation.

The members of the Working Group are all outstanding leaders in their fields and combine extensive experience in business, government, and academic life with expertise in science, technology, and industrial management. This report is the collective result of their considered opinions developed over an extended period of time rather than from their intense but brief examination of the issues in the context of the Working Group alone. Moreover, the recommendations result from the consideration of a much broader set of issues from which the issues selected were judged to have the most important national consequences and require Federal action. It should not be concluded, therefore, that issues omitted from this report are without merit.

On behalf of the Advisory Committee for Information Science and Technology, and of the National Science Foundation, we wish to express appreciation for the time and thoughtful consideration members of the Working Group brought to their task. It is our hope that the readers of this report will give serious attention to its message of opportunity and promise.

Joe B. Wyatt, Chairman Advisory Committee for Information Science and Technology, NSF	Howard L. Resnikoff, Director Division of Information Science and Technology, NSF

REPORT OF THE WORKING GROUP

1. Introduction. Civilization is based on the interplay between mind and muscle. Since James Watt's perfection of the steam engine 200 years ago, technology has concentrated on supplementing and replacing human muscle power by the power of energy-intensive machines. In the coming century technology will surely concentrate on supplementing and, in the more routine contexts, replacing human mental activity by the power of information-intensive machines.

There is no need to dwell upon the manifold changes in our life that information technology has already brought to pass. Telecommunications, including the telephone and television and mediated by the satellite, computers large and small, copying machines, videodisks, and other means for storing large quantities of information in an accessible form have in combination changed how and whether many of us work and play, created vast new industries and forced old ones into decline. A large and rapidly growing fraction of the American workforce derives its income from activities related to the production, communication, and transmission of information rather than from the production of material goods, and this trend will continue [9, 11, 15]. Automation of industrial production using intelligent robots, improvement of public education and workforce training by means of computer assisted instruction, growing international imports and exports of information [3], increased consumer and public access to information, and national defense are all increasingly dependent on advances in information technology, which has begun to assume the status of a national imperative. Heightened economic competition from our trading partners, the changing character of the workforce, computer crime, and problems of personal privacy are also products of the rapid changes in information technology.

This report concentrates on identifying aspects of information technology where research developments appear to be in the national interest but are unlikely to be pursued by the private sector for one reason or another. In these instances it seems appropriate that the Federal government play an active and supportive role in accelerating and coordinating the necessary developments. We have tried to set forth a general framework for decisions on Federal resource allocation which is broad enough to accommodate the rapid changes and varied implications characteristic of this new technology while still focussing on the several particular areas where we believe there are special prospects for high returns from moderate investment risks.

This Working Group is composed of engineers and scientists. Thus the reader will not be surprised to find that questions lying outside the technical sphere have generally been accorded slight attention in this report despite their evident importance. With regard to public policy issues, the forthcoming report of the National Academy of Sciences [14] complements this one. Other issues, especially those involving the societal impact of information technology, should be considered by appropriately constituted working groups.

The present time appears to be especially propitious for taking stock of the implications of information technology developments and the opportunities for the Nation inherent in them. The power of information processing machines has increased, and the costs have declined, to the point where machines which exhibit some degree of "intelligent" (i.e., decision making) behavior are spreading throughout society (cf. [12]). The convergence of computing and telecommunications technology is accelerating that dispersion. For instance, it is expected that 10 million Americans will be "on-line" by 1986, and 30 million by 1990. Thus it is not too soon to try to gain an overview of the opportunities ahead and of the gaps which may stall progress toward their realization. But it is also not yet too late for planned and coordinated activities of the private sector and the Federal government to fill those gaps.

The Working Group's recommendations call for more intense activities in eight general areas:

- Theory of Computation
- Knowledge Representation and Delivery
- Man-Machine Interface
- Software Production, Maintenance, and Obsolescence
- Very Large Databases
- Ultraparallel Hardware Designs
- Research Infrastructure
- Societal Impact

The following sections present brief descriptions of the eight general areas and identify particular problems within each one which seem to us to call for intensified effort. The discussion begins with the most general and abstract issues and proceeds to increasingly particular and practical ones. Although problems of the research infrastructure and societal implications, discussed in sections 8 and 9, lie outside the principal areas of expertise of the members of the Working Group, they are of such clear and pressing importance that we find ourselves obliged to draw attention to them, as others also have done.

Theory of Computation. Computational [illegible] lie at the root of all applications of information technology, so it is not surprising that theoretical investigations into the complexity of calculations should play a fundamental role. An early and decisive result—a triumph of pure thought—was the demonstration, about 50 years ago by the mathematician Goedel—that not every mathematical truth can be proved. This means that there are calculations which cannot be carried to completion by a computer no matter how powerful it may be. Such conclusions have profound philosophical implications but few practical consequences. They have, however, provided the incentive for recent research into the computational complexity of practical problems, and into the trade-offs between complexity and accuracy of computations for problems where some degree of error can be tolerated. The significant results which have already been obtained have immediate application to problems of data security and privacy. They have had a major influence in the area of optimization, and have greatly increased the size of problems that are routinely solved to improve the performance of various commercial, industrial, governmental, and academic operations and systems. Further progress will play a role in stochastic computation, in parallel computation, in the design of computers, and in structuring information processing problems so that their computational requirements can be efficiently met.

Because of its long-term nature and universal characteristics, research in the theory of computation is primarily conducted by university scientists and is supported by Federal grants. While the importance of continuing research in this area appears to be generally admitted, we believe that a more intense effort will repay the relatively small investment required and that the appropriate Federal agencies should encourage activity in this area.

3. Knowledge Representation and Delivery. At the present time, only biological systems can deal with complex knowledge problems. Nevertheless, the human brain appears to function as if it were, in effect, a complex, highly parallel computer. This establishes a fundamental link between the abstract considerations of the theory of computation and the more concrete but equally fundamental research questions related to how knowledge is represented in the brain and how it might be represented in the machine. The question of immediate practical interest, of course, is how to represent knowledge in a way that the machine can usefully manipulate and that seems natural to, and can easily be used by, a person.

As the complexity and performance of microelectronic circuits increase, more powerful ways to supplement and augment human performance in areas involving programming, decision making, design and analysis of experiments, and evaluation of data become possible. Equally important is progress in increasing the efficiency of communication across the man-machine interface by using higher-level information-bearing structures such as natural languages (in both written and spoken form) and graphic representations. The effectiveness of these methods depends to a large extent on the ability to transfer knowledge and information from one representational form to another and, ultimately, to classify and recognize patterns and representations of knowledge in a way which is compatible with, if not identical to, the way the human brain performs.

Research on these fundamental questions has begun although the number of workers is still small and the goal distant and ill-defined [1, 5]. Because of its long-term and basic nature, few private-sector companies have the resources or the motivation to invest heavily in the general problem of knowledge representation, although research on selected problems with a more immediate anticipated return on investment is being done. Amongst these are information retrieval and graphic display, and the use of artificial intelligence principles to develop "expert systems" for assisting professional knowledge-workers in specific tasks which involve the analysis and evaluation of large quantities of controlled data, such as assessing the economic potential of mineral deposits from geological survey data. These applications are beginning to prove their economic value, but they must be viewed as the products of a primitive "knowledge engineering" which thus far lacks the scientific base which would enable its full potential to be realized.

An understanding of the laws which govern the representation of knowledge, whether in the brain or in the machine, requires progress on a number of basic and intricate special problems, including:

- development of a general theory of pattern classification and recognition; and
- understanding the relationship between language and mental representations of knowledge, and in particular, between the structure of questions and stored knowledge.

Amongst the various sensory channels available to people for communication, the visual channel has by far the greatest capacity. This is the reason that graphic displays have become so popular in interactive man-machine communication. However, if information is communicated solely by displaying text in a natural language, then the high potential channel-capacity of the vision system is degraded so that the effective capacity is no greater than that of the speech channel. The introduction of images in addition to text, and in place of text, recaptures the advantages of the broadband vision system: those who said "one picture is worth a thousand words" knew whereof they spoke. Thus there are special research needs in the study of interactive graphic communication—especially in understanding how to substitute graphic and symbolic forms of communication for text and how graphical and image information should be organized for storage, retrieval, and display.

The Working Group believes that there is insufficient research in the broadly construed area of knowledge representation (and more broadly, artificial intelligence) and that existing efforts could be better focussed.

4. *Man-Machine Interface.* Dramatic improvements in the performance of computer-based systems have perhaps masked the fact that several areas have not made any basic or fundamental advances. Information machines are fast and precise and do not forget. People are slow and inaccurate and have a very limited capacity for short-term memory recall. Human information processing limitations are balanced by an exceptional ability to abstract, generalize, and synthesize. All of these are processes for reducing the channel capacity required to process information so that results can be obtained rapidly enough to be of use. These abilities also tend to reduce the significance of individual errors.

Contemporary computers cannot abstract, generalize, or synthesize to any significant degree. Thus the main problem concerning the man-machine interface is to make these two very different modes of information processing compatible; to "match the impedance" across the interface (in the engineer's jargon) in order to make it transparent and friendly, with the intent of enabling the machine to correct non-substantive operator mistakes, and otherwise forgive human errors, and to adapt itself to human thought processes rather than requiring the human user to use unnatural thought processes.

This problem is composed of a number of more specific research questions which appear to be receiving only limited attention. Since people normally communicate using spoken and written natural languages, a better understanding of how language can be used to communicate with machines is needed. It is particularly important to reduce the interface barrier for written materials in machine-readable form. Large amounts of text are now available in machine-readable form. As word processing systems become more widely adopted, the amount available as a by-product will rapidly increase. Its effective exploitation will depend on:

1. Recognition of the importance of providing standardized means for handling machine readable natural language text material;
2. Definitions of tasks and specifications for research leading to the design of general text handling systems;
3. Efficient software to perform the desired text handling functions;
4. Convenient human-factors-engineered terminals and desktop systems.

These factors lead to a number of general research topics.

Regarding the immediate future, it would be desirable to develop methods for the general retrieval of information and data items from text by word-processing systems. This could lead to widely dispersed and relatively inexpensive systems for the selective dissemination of information from locally created and maintained text collections.

In the area of the human interface, there are important research topics concerned with the evolution of existing techniques into more comfortable and natural machine systems, with emphasis on accessibility to non-specialist users and particularly on adaptive interfaces capable of becoming increasingly terse as the frequent user and the machine gain familiarity with each other. Their study would also help define the requirements for research in graphic displays, methods for storing graphic information, and internal systems useful for direct processing of graphic or pictorial data.

Some fundamental research on two-way interfaces other than the usual keyboards and cathode-ray tube displays should be encouraged to prod the development of more natural interfaces. This would include the exceptionally important natural language voice input and output systems, as well as more sophisticated tactile and visual communications means.

5. *Software Production, Maintenance, and Obsolescence.* Massive investments have been made in software prepared using "traditional" languages, and large staffs of programmers trained in them exist in commercial, industrial, and governmental organizations. Even research aimed at fundamental change in machine architecture is influenced by these facts.

For example, if highly parallel machine architectures become possible, the basic problem of providing software for such machines needs to be addressed. One approach has been to require that even machines with new and different architectures should be able to run software written in currently popular languages, instead of requiring special languages. That concept needs to be questioned. It might be more reasonable to have a combined research activity on architecture and software which attempts to keep the software problem within bounc [illegible]he software requirements could be kept within limits either by requesting that existing programming languages and programs be usable, or by minimizing the programming problem by the manner in which new machines are organized. Software languages need not be elementary. They need not be designed simply [illegible] beginner but can be intended to be efficient and comfortable to use at all levels of skill. A software system can be interpreted in a broader sense to include database systems which use interface characteristics and some internal, sophisticated levels of processing to permit extracting knowledge or information from data.

Through the years the fraction of total information systems costs devoted to software development and maintenance has been steadily increasing. The life-cycle costs of software are not clearly understood. The basic costs involved in developing a program in the first place are known to be very high. However, perhaps 75% of the total life cost of software is devoted to maintaining and updating existing programs. This problem may be particularly extreme within the Federal government, where procurement policies tend to favor retention of obsolescent hardware and the associated software inventory [4]. Thus research is needed on the economic consequences of various procurement and standardization policies.

The question of software development and maintenance is a research area whose economic implications will become of crucial importance as the national investment in software continues to grow and the fraction of total information systems costs devoted to it climbs even more rapidly. In these circumstances, obsolescing software capital may have economic consequences quite comparable to those of obsolescing steel mills or other manufacturing capital. Productivity may in fact become negative in the long-term maintenance of aging software. It is, however, important to recognize that despite the problems noted, the United States currently has a considerable competitive advantage with respect to other countries in software development. Efforts should be made to maintain and emphasize that advantage.

6. *Very Large Databases.* The *size* of a database is its dominant characteristic. Everyone knows that a shelf filled with books or a personal filing cabinet filled with documents is a convenient store of information to which the user has immediate access. But a large library or record facility, such as the more than 20-million volume Library of Congress (equivalent to about 2×10^{13} bytes of information) or the record storage division of a large corporation, can be as effective as encryption in foreclosing access to desired information unless it is equipped with sophisticated data management and information retrieval systems.

As the size of the database increases (and new high density low-cost storage means such as videodisks become generally available), the problems of designing adequate retrieval and management systems increase also. If the stored information is heterogeneous, as normal office records, scientific and technical information, etc. are, these problems become still more complex. They include at least the following:

1. How to verify the consistency of updates to an existing database.
2. How to make access to a database more natural, rather than through the tightly disciplined requirements cur[illegible]y typical of database systems, without unduly sacrificing system performance.
3. How to configure a system and represent data so as to increase the user's ability to extract information from the data.
4. How to develop methods for quantitatively analyzing the hardware, software, and performance costs of database management and information retrieval systems as part of the design process.
5. Discovery of optimum techniques for managing distributed databases.

A key area of current database research, in which major progress can be anticipated, is that of designing storage and retrieval arrangements that can support a variety of data models perceived by users, and the related issue of the ability to translate from one pre-existing database to another.

Some other research topics related to large databases are:

- Research in computational linguistics: automating the grammatical and meaningful manipulation of natural language.
- Research on typical intellectual and commercial use of information flows: where it is obtained and how it is used.

- Research on data structures: the computational efficiencies of different data representations and storage and retrieval structures.

7. Ultraparallel Hardware Designs. Research topics in the area of hardware can focus on a number of reasonably obvious directions. One would be in the area of components, and of the physical phenomena underlying new methods for implementing digital hardware systems. However, it appears that the commercial sector is vigorously pursuing this direction, and the capabilities and availability of integrated circuitry are well in advance of improved system and machine architectural concepts.

One interesting approach towards exploiting the availability of large numbers of microprocessors would be to explore the fundamental properties of highly parallel machines (cf. [13]). This is a natural extrapolation of current semiconductor technology. Computing systems composed of large numbers of identical elements are ideally suited for current techniques in semiconductor processing.

One objective of a highly parallel system would be to have processing power grow more or less linearly as processing elements are added. This would require a modest number of different types of elements, each designed to carry out a specific operation with great efficiency. If one were able to provide processing power directly in proportion to the addition of easily replicated hardware units, it would be feasible to evolve a family of variable-cost information systems, ranging from low to high, with proportionate or equivalent ranges in processing capabilities.

The development of parallel computers has proceeded in an evolutionary way since the early 1960's. Current NASA plans call for construction of a highly parallel computer adapted to fluid dynamics calculations, and the Japanese government has committed itself to the development of several still more powerful parallel machines. But these proposed architectures are specifically adapted for scientific computation and are unlikely to be well suited to such other important applications as data management, computer graphics, and other complex data-intensive processes.

The ability to put together large numbers of processing elements need not be confined to parallel machine architecture. Several research studies dealing with different concepts, such as array processors, variable threshold elements, highly redundant systems or so-called adaptive logic techniques have been undertaken during the past two decades. Nevertheless, because of the availability of inexpensive microprocessing elements the current practicability of implementing many of these systems makes it feasible for some of these alternatives to be tested and compared against each other on the basis of relatively pragmatic performance criteria.

A second area in which research into machine architecture could be encouraged is in various forms of memory organization, including well-known but as yet unsolved problems involving associative memories. Such memories could of course form one intelligent subsystem, where complex storage and retrieval processing is performed in an environment separate from the host computer itself.

There are certain categories of research for which currently available equipment is not appropriate and where parallel processors may afford special opportunities for a significant advance. Highly parallel processors whose architecture is specifically tailored for modelling neural and cognitive processing may provide a revolutionary advance in experimental opportunities for investigating representations of sensory information, and in particular, of the vision system. The photosensitive receptors in the human eye have a combined channel capacity of the order of 10^{10} bits per second; the foveal cones which mediate color vision have a channel capacity of about 10^9 bits per second. In order to simulate human vision information processing in real time (i.e., at the human rate) with a sequential computer, a machine having a cycle time of less than 10^{-10} - 10^{-12} sec. would appear to be required. The real-time requirement cannot be given up lightly, because certain applications wherein computer vision systems interact with a human operator in real time must operate at human speed. Current microcomputers have typical cycle times in the range 10^{-6} - 10^{-7} sec., which suggests that a highly parallel device consisting of 10^4 or more microprocessors may be necessary for meaningful real time computer experiments.

Information processing performed by the central nervous system is no less complex. Realistic simulations and experiments, whose results will also lead to improved models of neurophysiological and cognitive functioning, will demand even greater computing power. And it has already been remarked that the greatest potential gains from the use of information technology will continue to come from its use to supplement human mental activities. The provision of a radically more powerful tool for investigating cognitive and neural information processing is particularly important in accelerating progress toward that goal and toward a more realistic view of the true complexity of biological systems, especially the human brain.

In this section hardware aspects of parallel processing have been discussed. The time may be ripe for taking a revolutionary rather than an evolutionary step in the direction of parallel processing instrumentation for studying cognitive information processing and other complex computing tasks by undertaking to construct a machine consisting of as many as 10,000 microprocessors appropriately interconnected. This is within the capability of current technology and is a particularly attractive possibility because computing systems that are composed of large numbers of interactive elements are the kinds for which semiconductor technology is most suitable. Thus, from a hardware point of view, it is surely the best way of maximizing the computing power per dollar. The main problems which will be encountered concern how such a machine can be programmed to perform a useful range of tasks. We therefore strongly support studies undertaken to investigate the architecture and programming problems associated with such ultraparallel processors and, should their conclusions be promising, recommend that high priority be given to their construction.

8. Research Infrastructure. Research advances in information technology and related fields depend on an adequate supply of properly trained researchers and the availability of modern experimental equipment. Because of the explosive development of information processing in government and industry there has been a prolonged drain of trained investigators away from university research and teaching, so that research personnel are not being trained in sufficient numbers to supply current or anticipated needs. These problems have been described in detail for computer science [6] but they extend to the related fields of information science and cognitive science also.

This Working Group supports the conclusions of [6] applied to the broader context of all of the information and engineering sciences related to information technology, and recommends that this basic problem receive the urgent and coordinated attention of the Federal government, the universities, and the private sector, with the objective of finding cooperative means for alleviating it.

9. Societal Impact. So much has been written about the potential impact of information technology that we can hardly hope to break new ground. Nor are we experts in the disciplines which are normally concerned with such matters. Yet the implications of information technology for our Nation—indeed, for the world—are already becoming so portentous that we find ourselves obliged at least to identify certain topics which we believe should receive the attention of specialists in the relevant areas.

Information technology already augments and partially substitutes for mental activities, so that those who know how to use this new technology and have access to it are outdistancing those who do not know or do not have access. Thus the already large gap between the highly trained and educated and the untrained and uneducated, will grow, perhaps to dangerous proportions. Moreover, industrial and governmental employment will increasingly be limited to the more highly trained and technology-literate members of the workforce [15]. For these reasons we foresee a worsening education and training problem. Information technology can, of course, also be used to alleviate these problems through machine mediated instruction and training but these methods are not yet economically viable nor generally effective apart from some specific situations. We think that all aspects of this already serious and potentially critical problem deserve the most careful analysis and attention and that, in particular, the pace of research in the use of machines for instruction and training should be quickened.

Periods of pride, economic robustness, and optimism in America have historically resulted from or coincided with very strong technological leadership. During recent years the U.S. position relative to other developed countries has diminished and our ability to employ our advantages successfully has declined. It is not too soon for the United States to evaluate the consequences of living in an information age and to attempt to improve the Nation's future in this regard. Although waning in some areas, the U.S. position of leadership in information processing and associated computer based communication is well established and our stores of valuable information remain second to none.

But the heart of a policy of sustained leadership in the development of information technology and its broad application throughout American society is a national commitment to computer literacy. Consideration of this as an objective must be coupled to a serious assessment of the key technological advances and social adjustments which must be made should the Nation choose as a matter of policy to markedly increase the number of people who know how to use computers and other information machines. Previous sections of this report have identified many of the technological developments which would have to be in place.

Many Americans are certainly feeling the strains of accommodating to the information age. It is easy to wonder at what stage personal independence will be threatened as a result of inability to acquire, process, disperse, and store the information each of us will find necessary to remain competitive and employable, and how increased access to ever increasing stores of information can be reconciled with personal needs for privacy. These issues combine problems which, if not faced, may flourish, and opportunities which, if not grasped, may move beyond our reach. They deserve timely and serious attention.

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Report of the

WORKING GROUP ON THE CURRENT STATUS OF THE INTERFACE BETWEEN INFORMATION SCIENCE AND ECONOMICS

of the Advisory Committee for Information Science and Technology National Science Foundation

Summary: State of the Art

The economics of information and information science have been rapidly developing fields in recent years. They are concerned, broadly speaking, with the same questions. How should information be produced, conveyed, stored, retrieved and utilized? Who should have access to what information? What are the incentives for gathering and disseminating information? What are the consequences of the unequal distribution of information in the population?

Despite this commonality of interests, and despite a common mathematical heritage rooted in probability theory and convex analysis, there has been little scientific interaction between researchers in economics and in information science. The present manuscript is a survey, by economists, of the state of research on the economics of information, emphasizing those aspects most likely to be of interest to information scientists. We also present a brief discussion of the principal areas in which there are researchable open questions that would benefit from collaborative efforts between information scientists and economists.

Summary: Research Areas for Future Study

The brief summaries that follow are intended to be representative of the topics and questions in which economists and information scientists might find common ground. The background for each is given in the main part of this manuscript. In some cases, research in these directions is already under way.

Design of Organizations as Information Processing Systems

Economic theory has concentrated on assessing the value of information and the informational needs of organizations to achieve certain goals. It has been much weaker at developing the cost side. The study of the value of information arose naturally in conjunction with parallel developments in general equilibrium theory and statistical decision theory.

The costs of information have several origins: direct costs of gathering information, costs and errors due to aggregation and quantification, costs of transmission, coding and decoding, and costs of storage and retrieval. In each case, the purely technological aspect of these costs is comparatively minor, and is decreasing rapidly as new computer-based technology is implemented.

The larger part of costs is harder to measure. It lies on the man-machine interface, or within the fabric of the organizational structure itself. It may be all too easy to produce data relevant to a decision problem. What is difficult is verifying that these data are indeed the relevant variables, that they do not need to be modified in some way, that they are actually representative of what the decision makers are assuming, and more generally, performing the computation necessary to evaluate them. One well-known problem of this nature is informational overload.

Economists do not yet have an effective class of models for these issues. Two kinds of further work are needed. First, models of information transmission and utilization in organizations with a hierarchical structure are necessary. The function of hierarchies in economic theory, thus far, has been for the higher levels to monitor the behavior of the lower levels. Their roles as processors, filters and requisitioners of information have been neglected. Because the costs of information are intimately connected with the structure within which it will be utilized, these design problems should be studied in tandem.

Second, the economic consequence, and indeed the meaning, of better information should be examined. For a single decision maker, more information is obviously better, at least until the processing and evaluation limits of the decision maker are reached. But when the decision-making unit is an organization or system with disparate parts, improved information at the source may not result in an improvement at the stage of final utilization, and local optimization of the role of information may not coincide with global optimization.

Competitive Markets as Information Processing and Dissemination Systems

It is well understood that economic agents can use the observed market variables as a source of information that they do not directly possess. This idea has had a tremendous impact upon the theory of finance, where it leads to the "efficient-markets" hypothesis, and the theory of macroeconomics, where it is imbedded in the "rational expectations" theory.

Despite the fact that both theories have been extensively developed and tested, there is a great need for further work. These theories are in the tradition of equilibrium analysis. They ask, what would be the resulting allocation of resources if everyone knew the structure of the system and was capable of making costless and error free inferences from all the observable data. The process through which the structure of the system is ascertained is ignored.

The absence of any active learning from these theories may be the source of some recently discovered empirical paradoxes. Although the average return to those holding securities seems to be well explained by the efficient-markets hypothesis, the variability of returns is not. Asset prices seem to be much too volatile relative to their underlying determinants, such as dividends. It is certainly premature to assert that this discrepancy is due to the process of learning that accompanies the market transactions, but it is an interesting avenue to pursue.

Another area of potentially fruitful research would be to examine models where the endogenous market-determined variables convey some, but not all, of the information possessed by others. The decision as to whether to acquire the information directly or to accept the less accurate but presumably cheaper mode of making inferences from market variables is an interesting aspect of this problem. It becomes an important factor in the following way: as more people engage in active information-seeking, the better, presumably, will the endogenous variables reflect underlying information. Consequently, the lower will be the incentive to acquire it directly. Is there an equilibrium fraction of traders who engage in active information acquisition in this way? Is this equilibrium efficient, or should direct information acquisition be encouraged or discouraged?

Finally, research should be directed at the role of information as a commodity. The models discussed above have retained the traditional viewpoint that information acquisition and processing take place at the level of the decision-making unit, but that information is not otherwise bought and sold. The issues of reliability, privacy and quantifiability of information are important here. These topics are related to, and logically prior to, an evaluation of the economic value-added of the information processing sector and of innovations in information technology.

Public Information Quality

Recent research in economic theory has made possible the modelling of processes such as auctions where the information available to the participants has an important influence on the outcome. Similarly, the publicly available information embedded in crop forecasts and in inventory levels for grains is an important determinant of futures market prices, and hence of the allocation of agricultural resources.

The theories currently available are highly simplified. They assume, for example, that the object being auctioned has the same ultimate value to all possible purchasers. Their conclusions about the value of improving information may be sensitive to these assumptions. Further work is needed to develop usable procedures for evaluating the impact of changing the information made publicly available, or for changing the auction rules or market-structure itself.

THE CURRENT STATUS OF THE INTERFACE BETWEEN INFORMATION SCIENCE AND ECONOMICS

1. Introduction

Acquiring and using information is a cornerstone of economic activity. In order to channel resources to their most productive ends, needs and capabilities must be identified. Incentives must be created for individuals to coordinate their activities and to willingly pool their information. Institutions, such as contract-enforcement, organizational structures and communication links, must be established and controlled in order for the system to function smoothly. All these aspects of economic behavior require information and may be impeded by its absence or its inaccuracy.

As our economy becomes increasingly complex the demands for more, better and faster information grow dramatically. The institutions in our economy are shaped by informational considerations, and conversely, induce demands for superior information processing and transmission. Economic activity and information processing are symbiotic.

For these reasons, the availability of information and the ability to evaluate it quickly, accurately, and at a reasonable cost are important goals for national economic policy. Information science and economic science are natural partners in any systematic study of the effects of informational policies or technological improvements. Their common mathematical roots make collaborative research possible, and such efforts are long overdue.

The economics of information, as an academic subject, predates the data processing revolution. In the last 15 years, however, its development has accelerated markedly. Uncertainty is pervasive in the economic environment. As economists came to recognize its effects, and the way in which it has shaped our institutions, many diverse problems have been viewed in a new light. Issues such as discrimination in employment, efficiency losses from taxation and competitive bidding for contracts—previously analyzed in rather *ad hoc* ways—have now been analyzed in a common framework. They are all consequences of informational asymmetries among individuals. The pooling of information and risks has been studied in finance and in the economics of insurance. The commonality of interests created by the formation of business firms has long been regarded as their *raison d'etre* and as their source of innovative potential. The desire to mitigate or share risks while maintaining strong economic incentives lies behind many long-term contractual relationships. This has received much recent attention under the names of "principal-agent problems" and the theory of "implicit contracts." Indeed, were there no uncertainty at all, economics and information science would both be rather dull subjects.

The growth of the economics of information and uncertainty as a unified discipline has been greatly enhanced by the interaction between mathematics, statistics, and economics. In addition to these fields, economists will benefit from intellectual contact with communications engineers, computer scientists, psychologists and others concerned with the impact of the electronics age upon our society. Likewise, we believe that many of these "information scientists" will find the economists' problems interesting and useful in their own areas as well. It is our hope that the selective survey and overview presented below will help forge a strong link between economics and infomation science.

One source of the widespread interest in the economics of information can be traced to the so-called market socialism debate of the prewar era. The issue was whether a socialist economy could attain an efficient allocation of resources through market-like mechanisms with the planning process. It might seem that, given identical technologies, these systems differ primarily in their ability to discover and disseminate information efficiently and in their potential to create incentives for individuals to implement socially desirable plans. In this context, it is therefore natural to focus attention on the questions: How do the limitations of imperfect and dispersed information, compounded with conflicting individual incentives, restrict the allocations attainable by mechanisms of this type? To what extent are they inferior to those attainable under complete information and fully centralized control? What is the best way to design the mechanisms, before learning the parameters of the economy, so as to optimize some objective function? And how stable is this type of mechanism to "environmental" change?

The second major impetus to work on the interface between information processing and economics is the predictability of economic fluctuations. This has fascinated economists and businessmen for centuries. Needless to say, fortunes can be made on the basis of superior predictions—and can be lost by erroneous ones. It is only recently, however, that the interplay between prediction and observation has been explored on a rigorous mathematical basis. These considerations have also been brought to bear on policy-relevant discussions. What information is necessary in order to stabilize the economy, or particular sectors of the economy? What is the effect of financial disclosure regulations and other privacy-related legislation? To what extent do such policies enhance or diminish the useful character of economic data collection and data processing?

Third, there are the questions of the specific effects and costs of information gathering and information dissemination on the economic activity in particular markets or sectors. Active information gathering strategies are important in auction markets, such as those for treasury bills and oil leases, as well as in more traditional markets such as those for agricultural products and currency. Issues of privacy, such as credit information or the details of corporations' financial positions are further examples of the pervasive conflict between the value of improved information and its costs. The information processing revolution has, at the same time, opened vast opportunities for the use and misuse of information, and changed the relative costs of information acquisition and evaluation, and of both of these compared with other decision-making costs.

The summary of the state of the art that follows is organized along the lines of this brief introduction. In the next section we discuss the normative issues of the design and performance of allocation and decision processes to operate in the milieu of imperfect information characteristic of actual economies. Then we will discuss the problems of prediction and the rationality of expectations. Finally we address some concrete models of the interaction of economic agents in uncertain environments. Particular attention will be focused on the effects of improving their private information about the state of the system. Along the way we hope to point out some areas lying close to the interface between economics and information science where interaction across these disciplines may be particularly fruitful.

2. Economic Organization and Information Science

Economic systems have many close parallels with information processing systems. Both can be shaped by conscious design to function in environments whose general characteristics are known, but whose details vary from one instance to another. For example, inventory control systems are based on the idea that sales follow a stochastic process with known parameters. At any moment, the state of the system determines its responses: adjust production, order supplies, etc. In general information processing, the nature of the data and the use to which it will be put is important in system design. The tradeoff between flexibility (i.e., universality of processing algorithms) and efficiency is central to the design both of economic systems and information processing systems.

There are, however, several important special features of the design problem in economics. Economic systems must deal with the diversity of interests of their members, as well as with the problems of imperfect information. These two facets of the problem interact, each hampering the solution of the other. Were information perfect and communication costless, conflicts of interest could be resolved by a system of enforceable contracts. Conversely, if all individuals shared common goals, the problems of choosing optimal actions under incomplete information would amount to a certain type of constrained optimization. The confluence of these two problems is often absent in pure information processing situations, and in this case one can consider the information processing problem as a kind of generalized information retrieval. In many applications, however, such as systems designed for accounting and financial control, and the so-called "expert systems," the "economic" aspects of the problem give rise to both the issues of diverse objectives and dispersed information.

The compounding of incentives-related difficulties with the purely informational problems makes it best to proceed in a step-by-step fashion in presenting a summary of related research. We will deal first with the informational issues, assuming the members of the system agree about objectives. Then, issues of divergent payoffs will be addressed, but still retaining the hypothesis that the communication process can be prescribed. Finally we allow for both conflicts of interest and strategic behavior in the transmission of information.

The costs of acquiring and processing information, in contrast to its benefits and effects, is much less well understood by economists. Part of the problem is that we do not have good theoretical models of the economic utilization of discretized information, or information (such as cross-referenced indexes) that is not easily quantified. Much further work needs to be done in this area.

A. *Designing Organizations in the Absence of Conflicting Objectives: Team Theory*

The theory of teams was developed by J. Marschak and R. Radner[1] (1972) in the early 1950's. A team is an organization with a well-specified objective, shared by all members, in which actions and information are necessarily decentralized. Each member is responsible for some component of the team action, and each has access to possibly different initial information. Communication can improve the payoff but by hypothesis, channels for such communication are costly. The central goal of team theory was to compare different communication designs. Which systems achieve a high expected payoff for a given informational effort?

The theory stopped short of this goal. It proved too difficult to develop useful measures of "informational effort." Instead attention focused on the optimal utilization of some fixed information structure. Team theory characterized the best team decision rule for a given information structure. The signals which a member observes in a given information structure may be obtained through messages received from others or through direct observation. The rule specifies what action is to be taken given these observations.

The principal results of team theory deal with several special cases. When the payoff function of the team is quadratic in the actions of its members, and when the unknown parameters of this function are jointly normally distributed with some observable variables, an explicit solution can be obtained. The action taken by each member is a linear function of his observations and of the observations of others that are transmitted to him. This linear-quadratic structure is reminiscent of results in stochastic control theory, the corresponding single-person decision problem. Another special case, of significant economic importance, is the problem of the centralized allocation of a fixed quantity of a scarce resource among the members of the team combined with "local" inputs whose utilization is determined separately by each team member.* The principal issue in this problem is that the "local" decisions are not perfectly coordinated because each team member lacks full knowledge of the random parameters relevant to the others. The loss due to this informational incompleteness has been analyzed. It has been shown that it falls as the number of team members increases. Essentially, the team's optimal decision rules can rely on the law of large numbers to reduce the impact of uncertainty.

B. *Designing Organizations in the Presence of Conflicting Objectives but Non-Strategic Behavior*

The study of market-oriented mechanisms for allocating resources uses the same methodology as team theory. It is based largely on the hypothesis that consumption is private and therefore that scarce resources must be allocated among competitive uses. This has been stimulated by the economists' traditional preoccupation with the workings and the claimed optimality of an idealized version of a price-guided market-oriented economy. By 1950, due to the work of A. P. Lerner[2] (1937) (1946), O. Lange 1942[3], K. J. Arrow (1951a)[4] and T. C. Koopmans (1951) (1957)[5], economists had been able to show under what assumptions concerning the economic environment perfectly competitive equilibria are optimal and every optimal allocation is achievable as an equilibrium of the economy with a suitably chosen income distribution. The interest in such results was due in part to the belief in certain desirable informational characteristics of the competitive mechanism. It seems highly decentralized in that each individual or firm need only know its own economic characteristics plus the market prices. In this way it seems superior to the more highly centralized procedures of a "planned" or "command" economy.

To approach such questions it was necessary to formalize the informational aspects of the market mechanisms, particularly the meaning of decentralization. A rigorous concept of an abstract economic organization, or mechanism, was introduced by Hurwicz. The perfectly competitive structure is one special case of a mechanism, but there are many others.

The Hurwicz framework modeled the process of resource allocation as a system of difference equations describing the communication among the individuals in the economy. Formally, a mechanism is a triple consisting of the message space, the response rules, and the outcome rule.

The message space represents the language in terms of which agents communicate. A given agent's response specifies the message this agent will emit given the messages previously received and given his information about the economic environment. Finally, the outcome rule specifies the resource allocation (or allocations) that will prevail once the dynamic process of message transmittal has reached a stationary value.

With this formulation of a class of economic mechanisms it became possible to define various aspects of its performance. "Non-wastefulness" described mechanisms for which all outcomes generated by stationary messages were necessarily optimal. The informational decentralization property, called "privacy-preserving" specified that a given agent's response

*This is, in essence, the problem faced in the distribution of central computing power to time-shared terminals. At a higher level, it is also reflected in the architecture of the computer's central processing unit, and in the design of telecommunications systems.

function is independent of other agents' characteristics; i.e., to determine the next message to be emitted, the agent only needs to know his/her own characteristics but not those of other agents. In this formalization, the perfectly competitive mechanism is both "non-wasteful" and "privacy-preserving."

This framework has been widely used to formulate questions concerning the theoretical limits to performance of mechanisms having various informational properties. For example, are there mechanisms other than the perfectly competitive one that share its non-wasteful and privacy-preserving features but which require smaller message spaces? Are there others that use a space of the same size but can achieve different results?

The answers to characterization questions like these depend on the domain of economic environments over which the mechanism is to be applied. The specification of this domain amounts to the planner's admission of the range of his *a priori* ignorance of the data of economy. To date, economic theory has handled this issue in a rather non-parametric fashion. Domains of economies are specified by giving qualitative properties of agent's characteristics, such as convexity or differentiability of their utility functions, rather than by placing quantitative bounds on attributes such as endowments or demand elasticities. Insofar as the theory has achieved the result that an optimal resource allocation is achievable, that is that the limitations on communication do not in fact lead to an inferior realization, this non-parametric approach has been successful. Future research, where a greater degree of ignorance by the designer is recognized, may benefit from an alternative methodology.

The parallel between systems design and this branch of economic theory is that of the specification of the performance function to be implemented. The economic planner can be thought to describe the outcome to be achieved for every environment in some domain. In this framework, Hurwicz, Reiter and Saari have given a constructive mathematical method to find the adjustment process of minimal dimension which realizes this performance.

C. Designing Processes to Implement Social Objectives in the Presence of Strategic Behavior

The previous section dealt with resource allocation in the presence of differing evaluation of outcomes by the economic agents. But though their goals were in partial conflict they were not assumed to distort their private information so as to manipulate the mechanism to their own advantage. Honest behavior was assumed. In this section we consider some of the recent attempts to design mechanisms that achieve good outcomes, even in the presence of such strategic behavior. As a simplifying, and extreme, benchmark we will assume that individuals take full advantage of their ability to control the outcome by strategic play. Honesty for its own sake, or morality, is assumed to play no role.

With any mechanism in place, the economic system is converted in the formal sense into a game. Strategies of an agent are his responses to the mechanism and his transmission of private information to other individuals. We are interested in the equilibria of these games. Different mechanisms will have different equilibria.

The choice among mechanisms is complicated by the possibility of multiple equilibria common throughout all of game theory. The strongest kind of solution is an equilibrium in dominant strategies—when each player has a best action independent of all others. In general, mechanisms cannot be designed to achieve optimal outcomes and have dominant strategy equilibria.

If one gives up on the ideal of implementing outcomes in dominant strategies, much more can be achieved with somewhat weaker solution concepts. In the case of finitely many alternatives, it has been shown that any desirable outcome can be implemented as the Nash equilibrium of a game constructed by the mechanism's designer, if he is free to choose suitable large and complex strategy spaces. With constraints on the complexity of strategy spaces only, somewhat weaker results are possible.

D. A Reassessment of the Treatment of Informational Costs in Resource Allocation Mechanisms from the Point of View of Information Science

As path-breaking as the models discussed in the last several sections are, there are still three distinct ways in which they oversimplify the assessment of organizational costs. (1) They treat a price-mechanism for an economy as, in effect, a "one-step" design, in which observations are made, messages are announced (prices and proposed trades), and then—*if* those messages characterize a competitive equilibrium for the economy—actions (trades, productions, consumptions) take place. One suppresses the many steps which in fact might be needed to attain an equilibrium. (2) Only one information cost—that of message transmission—has been considered and it has been given one principal measure, namely dimension of the message space. (3) The price mechanism is compared (with regard to message-space dimension) *only* with designs that achieve exactly what the price mechanism achieves, namely an optimal resource allocation for each environment. The work so far completed does not permit the trading of benefits against costs. Little work has been done on *approximations* to the price mechanism, even though such approximations are clearly required in practice. We do not yet know the informational costs of a design which *approximates* the price mechanism to a given precision, with the approximate mechanism's actions falling short of the optimal resource allocation achieved by the "true" price mechanism. If those costs were devoted instead to other designs, would all such alternative and equally costly designs achieve a lower (or at least not higher) benefit than the given approximate price mechanism?

One approach is to discretize the space of decisions and messages, rather than assuming each to be a continuum as in the work cited thus far. In that case decision errors are unavoidable and instead of requiring optimality one seeks privacy-preserving mechanisms which achieve the lowest error permitted by the given discrete spaces.

All of the models discussed above neglect the computational sophistication required of the individual agents in an organization. Limited abilities and costly or error ridden computations are nonetheless important in practical design problems. One can sometimes lower the dimensionality of message spaces by requiring more complex response rules. It is thus important to be able to compare processes in terms of computational complexity, as well as on their other characteristics. Conversely, an increase in dimensionality can reduce the error rate, as for example in computers carrying "check digits."

There is a large literature in computer science and mathematics dealing with complexity of computations. At present, economists have not made use of this theory in the context of allocation mechanisms, although it seems relevant at an intuitive level. Perhaps the problem is that in some aspects this theory is too "fine," calling for more detailed information than is available, while in other aspects it is too "coarse," admitting too few kinds of computational problems. What is needed is an approach which uses the type of information available in allocation models, e.g. environmental parameters, performance functions and message correspondences, and permits analysis showing relationships between computational complexity and other informational costs or constraints.

Futia[6] has studied complexity of decision rules in an economic setting using the algebraic theory of sequential machines particularly the Kron-Rhodes Theorem. Mount and Reiter[7] have used an approach combining the "neural network" model of McCullough and Pitts[8] with an explicit formulation of the computational task associated with a privacy preserving allocation mechanism. Via an example they show that enlarging the message space permits a reduction in computational "cost," while preserving performance.

In addition to computing costs, other informational costs confront the designer of organizations, and there are a number of possible approaches to measuring them. One may break the operation of a design into the *tasks* of observing, message-sending, computing, action-taking, or possibly storage and retrieval required of the organization's members. Different approaches to cost measurement correspond to different views of the *technology* of each task. Individual theories, which characterize the technology of certain of these tasks exist but none has been developed as part of a unified effort to compare the costs and benefits of designs.

A task can be viewed as the assigning of an output (a message, an action a computational result) from a set of possible outputs, to an input (a message, an observation) obtained from a set of possible inputs. Models of the technology of such a task may be loosely divided into three families:

(i) Deterministic investment-cost-only models, wherein a device to perform the task is acquired once-and-for-all; the device stands ready to deal with all of the task's possible inputs. There is no separate charge for each successive output-to-input assignment and the probability distribution of inputs plays no role.

(ii) Frequency-exploiting investment-cost-only models. Here there is again no separate charge for each output-to-input assignment, but the device used takes advantage of the fact that some inputs occur more frequently than others.

(iii) Models in which a different cost is incurred for each input-output pair, and is assessed when that pair occurs.

For the case of a computing task, the models of finite-state machine theory are of the first type. For the case of a message-sending task, the models studied in the earlier Shannon theory are of the second type. Codes are used to exploit frequency differences and to economize on channel size, as measured in symbols per time unit; and it is channel size, a once-and-for-all fixed investment, which determines the task's costs.

Much current research in computer science fits into the general framework just discussed. A computer, or a computer network, may be modelled as an organization, whose "members" include terminals, compilers, memory units, and arithmetic units. Designing software which permits the given installation to compute certain functions while providing a good balance between performance (accuracy) and cost (time) is a problem of efficient design in the sense just described. Research on various topics which appear under the labels "parallel processing," "distributed systems" and "resource-bounded computation" appear closely related to the economists' organization design problem. On the other hand, to solve a resource-allocation problem by means of a price mechanism may formally be viewed as the use of a parallel algorithm, with individual agents playing the role of simultaneously functioning processors. Research in which there is a dialogue, if not active collaboration, between computer scientists and economists concerned with informationally efficient resource-allocating designs has never been attempted. It may be an effort whose time has come.

Some current work in transmission and coding theory has gone well beyond the economically unmotivated results of the early Shannon theory. In studying a sender, who observes a source of repeated signals and is to inform a receiver about them, specific attention is now paid to what economists would call an "efficient surface." This is a surface in a space whose dimensions include channel size (in symbols per time unit), size of the block of messages which accumulates before coding and transmission and expected value of a "fidelity" criterion. The fidelity criterion is some function of the source signal and of the receiver's inference about the signal, a function more general than the simple "error" of the early Shannon theory. Again, however, collaboration between "information theorists" (as they still tend to be called) and economists interested in resource-allocating designs is lacking.

With regard to the task of observing, it might turn out that certain work in the field of pattern recognition is suggestive for the efficient-design problem. Dialogue and collaborative efforts might well be explored.[9]

Technological advances during the past twenty years have dramatically reduced information processing costs. This has naturally led to the birth and rapid growth of entirely new branches of the computer manufacturing and software industries. The economic consequences of this revolution in information technology go far beyond those related to industrial growth. Information can now be collected, analyzed, and disseminated in such large quantities and with such speed as to substantially alter the decision-making processes of consumers and producers. Economic choices can now be made after a careful consideration of far more alternatives and with far more attention to future economic events than has ever before been possible. Will this dramatic increase in information processing capacity change the behavior of producers and consumers in ways which will irreversibly alter the performance of the market system? Can the fruits of the information revolution be utilized to improve the allocation of resources within our economy?

3. Prediction and Information Transmission through Competitive Markets Forecasting in Self-Affecting Systems

Economic forecasts are made to be used, and decisions based on them can affect the predicted events. Forecasts can be self-fulfilling as in the case of a predicted stock price increase, or self-defeating as in the case of a predicted energy shortage which leads to increased conservation and the development of alternative energy sources. This problem was originally thought to be a major impediment to the development of predictive economic models.[10] However, over the past two decades many econometricians have resolved this difficulty by including the responses of rational statistical decision makers in "rational expectations" econometric models.

More recent research has unearthed a new and somewhat deeper conceptual problem involving the relation between the beliefs of economic decision makers and the extent to which their decisions reveal the fundamental variables of the economy. A change in economic conditions may affect a decision unit's set of feasible alternatives and also the desirability of alternatives within that set. As most economic data are price and quantity data generated by market transactions, they reveal the underlying structure only imperfectly. Forecasts influence transactions and these observations. In this way they influence the knowledge on which successive forecasts will be based.

These interactions between learning and the system being learned lead to a rather different view of empirical inference than is appropriate in other fields of scientific inquiry. This is not to suggest that empirical inference in economics is inherently limited or that a new theory of statistical prediction must be invented for economics. Recent research has concentrated on identifying those economic information structures which are consistent with conventional methods of inference.

B. Information Flows and Their Sufficiency

There is a classical doctrine in the theory of competition which holds that in a market economy prices alone provide decision makers with all the information about the rest of the economy needed to reach optimal decisions.[11] This doctrine does not envisage the interaction between knowledge and observation, and many researchers have found in the latter problem a deeper application and stronger test of the classical doctrine than was previously possible. A major initial finding has been that the classical doctrine is essentially correct provided that the existing range of financial markets is complete.[12] "Completeness" here means that the set of investment opportunities should be sufficiently diverse so that full insurance against economic risks is possible. For example, a faculty member of a state university should be able to insure his future income by investing in a portfolio whose return is exactly inversely correlated with the tax revenues of the state. Under this condition prices alone transmit all decision-relevant information, although as we have stressed above, prices reveal little of the underlying fundamental variables.

While existence of a complete range of financial markets is an ideal not met in practice, it is plausible that prices disseminate much of the relevant information. On this point, however, substantial theoretical problems have arisen with the equilibrium concept itself. Indeed, it appears conceptually possible that with incomplete markets the interaction between knowledge and observation may disrupt any systematic method of inference from prices.[13] The question is still far from settled and research in this area is quite active.[14]

The actual construction of economic forecasts, when it is known that these forecasts influence the behavior of the system itself, poses a new set of questions. The preliminary results suggest that conventional methods of statistical estimation may still be applicable, although the small sample behavior of the estimates will differ substantially from that described in the theory of statistics. This area represents a potentially fertile ground for collaboration between economists, statisticians, and information scientists.

C. Policy Applications of Information-based Economic Models

One of the most important applications of rational expectations models has been to examine the role of the economy's information structure in generating business cycle fluctuations. Do emerging technologies permit changes in the information structure of sufficient scope to smooth business cycle fluctuations? A convincing answer to this question will require research along a number of barely explored avenues. We will now sketch the current state of our understanding of the connections between business cycles and information and, along the way, point out several important research problems.

A puzzling feature of business cycle fluctuations is the observed negative correlation between the rate of inflation and the rate of unemployment which is depicted by the so-called Phillips[15] curve (1958). During the 1950's and

1960's many economists believed that this correlation reflected a stable "tradeoff" which policy makers could exploit to achieve an inflation-fueled prosperity. But in one of the most influential papers published in macroeconomic theory during the past twenty years R. E. Lucas (1972)[16] demonstrated that this tradeoff was likely to be more illusion than fact. His explanation is based on the imperfect ability of economic agents to identify the component of price changes that is "real," rather than of purely monetary origin. The presence of this signal extraction problem causes the equilibria to exhibit the Phillips curve relation, but it cannot be exploited by a systematic policy.

Some economists dismiss the idea that economic agents can be so ill-informed about current and future relative prices as to generate output fluctuations of the magnitudes typically observed in the last several decades. They point out that information technologies have reached the stage where "complete" information is an attainable goal. If producers and consumers choose not to employ these technologies then it must be that the private benefits do not justify the costs; thus business cycle fluctuations do not imply an inefficient allocation of resources.

This objection is open to the criticism that it ignores a potentially serious problem of information externalities. If the decision to acquire more information indeed results in more "stable" equilibrium time series, reflecting only real rather than monetary factors, then all economic agents will benefit from the resulting reduction in uncertainty. However, these external benefits do not enter into the cost-benefit calculus of individual agents. Underinvestment in information may well result.

To determine whether this is a serious problem will require the development of macroeconomic models in which the decision to acquire information is endogenously determined. Some progress along these lines has already been made. But the appropriate analysis of economic welfare gains or losses requires business cycle models based more closely upon the maximizing behavior of risk averse economic agents.

There is another related issue which is also poorly understood. The emerging theories of the business cycle stimulated by Lucas' paper all rely upon divergences among economic agents' forecasts to generate business fluctuations. That such divergences exist is easy to document, especially in the financial and commodity markets and also among macroeconomic forecasters. Yet in all these cases it is difficult to attribute the divergences in expectations primarily to differences in the information available to different agents. Indeed, all macroeconomic forecasters have access to virtually the same set of publicly available data. Yet from this data set they infer different (sometimes radically different) models of the economy.

It is probably the case that this diversity in forecasting models is the principal source of the divergent expectations held by economic agents. If policy actions designed to alter information structures and thus affect business cycle fluctuations are to achieve their goals, they must somehow also reduce the diversity observed in the economic forecasting models. To determine whether this is likely to happen it is necessary to have a theory of model formulation and evaluation in which information availability plays a central role. This theory should predict the conditions under which model diversity can be expected to increase, persist or be reduced. Such a theory should, for example, provide guidance on the effects of a significant change in information availability. Will the added information stimulate model-builders to explore entirely new possibilities, thus increasing model diversity, or will it instead permit decisive tests of competing models, thus reducing diversity?

D. *Information and Behavior under Uncertainty*

The economic model developed by Lucas (op. cit., 1972) is one of general economic equilibrium under uncertainty. But despite its structural simplicity Lucas was unable to determine whether or not there was some monetary policy rule which could offset the information deficiencies and thus reduce or eliminate the model's output fluctuations. For in order to answer this sort of question one generally must be able to derive explicit expressions for the stochastic equilibrium time series. This is not usually possible if there are any significant non-linearities present in the model's structure.

The obvious solution to this difficulty is to forego the analysis of models based upon the utility maximizing behavior of risk averse agents and instead work within a linear, certainty-equivalence, framework in which risk preferences play no role. The first major example of this approach in the macroeconomic literature appeared in a controversial paper by Sargent and Wallace (1975).[17] It develops a linear macroeconomic model which incorporates Lucas' supply hypothesis, i.e. that output fluctuations occur only when price fluctuations are misperceived as arising from real demand shifts. Sargent and Wallace demonstrated that any monetary policy rule which permits economic agents to anticipate the future changes in the money supply will have absolutely no effect upon real variables.

This is a remarkable result. However, it has widely been misinterpreted as indicating that the hypothesis of rational expectations precludes monetary or fiscal policies from having effects upon real variables. But in fact the Sargent-Wallace result arises solely from the specific information structure they assumed. This point was made by Weiss (1980)[18] who demonstrated that under an altered information structure, monetary policy can be effective. In fact, he exhibited a policy based only upon publicly available information which alleviated informational deficiencies structural to the economic system.

The literature cited thus far contains many new insights into the role played by information and communication in macroeconomic fluctuations. Yet this "linear models" literature has a serious weakness. Its behavioral relationships are based upon the certainty equivalency hypothesis which asserts that only the expected values of random variables (but not their riskiness) affect economic decisions. This hypothesis should cause one to be skeptical of the conclusions these models reach about the possibility of smoothing output fluctuations through systematic monetary or fiscal policies. For such policies will affect the riskiness inherent in the economy's equilibrium time series. This in turn will change the apparent elasticity of economic agents' responses to changes in the expected values of the random variables they forecast. In other words, the demand elasticities of risk averse agents are actually endogenously determined by the riskiness of the equilibrium time series; in contrast, a linear model assumes that these elasticities are exogenously given and fixed.

In (1980) Futia[19] offers a critique of the certainty equivalence hypothesis and shows that it can be seriously misleading. The ranking of the variance of the equilibrium time series associated with two distinct information policies is reversed as soon as one introduces elementary considerations of risk aversion into an otherwise linear model. This underlines the need to study the properties of "almost linear" macroeconomic models which incorporate the implications of risk averse behavior so that we can begin to understand the possible consequences of macroeconomic stabilization policies.

E. Information as a Commodity

Given the importance of the information processing industry in the modern economy, it is surprising that there is virtually no work in the economics of information as a commodity. Part of the reason for this gap is that to value information one must know what decision problem is being faced. Without this, the demand for information cannot be determined. But as the previous sections have shown, any available information is likely to "leak out" via the price formation process. Equilibrium theories in economics (which are all we have at present), by definition, cannot capture the advantage possessed by the original recipient of knowledge over those who learn only indirectly.

As for the supply side, a few facts are obvious, but their implications are hard to follow up. Information is thought to be costly to discover but relatively cheap to duplicate in transmission. It is the quintessential decreasing cost industry. But if proprietary information is valuable only insofar as few people have it, the supplier should try to convince his buyers that only a limited number of others will receive it. However, although this may be possible at the first stage, it becomes increasingly difficult to insure that the buyers do not, in turn, duplicate and sell it.

Other aspects of information as a commodity are equally fascinating but even harder to model in economic terms. Nevertheless our discussion would be incomplete without them.

Privacy, the lack of certain information or access to it, is costly to misuse and is certainly desired by many people. In the computerized world it is often easy to access personal and financial information simply by obtaining a few identification numbers. It would be interesting to estimate the value of privacy and the costs of providing it.

Much of our discussion of information concerns the occurrence or non-occurrence of exogenous events. Yet much of the output of the information processing industry is actually a condensation of information. Data in its raw form is often unwieldy and not useful. Computers have made it possible to access particular pieces of data or to extract summary statistics that make the data more useful. Formally speaking, these are less informative than all the data rather than more informative. Data compression or extraction is economically valuable because the costs of computation and analysis are real costs.

Finally, much of what one considers important in the assessment of information as a commodity is hard to cast in the mold of decision theory at all. The purchaser does not have a clear idea of the space in which the events in question lie. Rather, what he is buying represents a mold in which further questions can be asked, or it calls the buyer's attention to a perhaps overlooked aspect of his decision problem, or to an error he has made. Just because these issues lie outside the usual bounds of information science and economics does not mean that fruitful insights could not be obtained if investigators were to direct their attention to them.

In conclusion, the relation between the expectations of decision makers and the information carried by economic data has forced a fundamental reconsideration of empirical inference in economics. Most economic data are price and quantity data which are generated not for the purpose of scientific observation but to guide the allocation of resources. Emerging results indicate that forecasting may be logically impossible unless the observed data constitute a complete set of allocation signals. The state of the research in this area leaves many tantalizing open questions on both the theoretical and empirical planes.

4. The Value of Improving Public and Private Information

A. The Effects of Changing Information Quality

The preceding sections of this essay have all taken the structure of exogenous information as given, and have traced its effects on the economic system. In this section we discuss the effects of improving the quality of information available. Such improvements can take the form of more accurate observations, more rapid communication or calculations, or new sources of knowledge.

In single-person statistical decision theory the concept of "more informative" is defined as a way of comparing information structures. It is due to Blackwell[20] (1951) and Bohnenblust, Shapley and Sherman (1949).[21] Information structure A is said to be more informative than information structure B if, for any decision problem, the decision-maker would prefer having access to A rather than B. This relationship is a partial ordering; for many pairs (A,B) one's choice would depend on the problem at hand.

In economic problems, or in multi-player decision problems more generally, there is an additional complication to consider. The players have (partially) conflicting goals. Their behavior is not perfectly coordinated. Changing the information structure may lead to new problems of coordination, or new adverse incentives. Effectively, the decision problem faced by the system, viewed as a whole, may have shifted. One cannot separate the information structure from the problem to be solved, as in the one player case.

Because of this difficulty it is impossible to find definitive rankings among information structures in general multi-person situations. Examples in which complete ignorance dominates an informative observation are known. Therefore, the research avenue that has been pursued is to narrow the class of problems over which one requires the dominance of one information structure over another. For example, players' payoff functions may be assumed to belong to a simple parametric class. Alternatively, their payoffs are identical but their prior probabilistic beliefs may be different.

In summary, a partial ordering of information structures can be defined in multi-player settings. One information structure is said to be more informative than another if, for the class of problems at hand, the model predicts a higher expected payoff when the former structure is operative.

This type of analysis has been conducted in three distinct kinds of models: market models with a large number of traders; auction models, where the number of potential bidders is common knowledge; and two person games. In each case the goal has been to find classes of models for which, when information improves in the sense of single-person decision theory, it improves payoff values in the situation being studied as well. The remainder of this section addresses these three kinds of models.

A tremendous explosion in the processing of information relevant to market transactions has taken place in recent years. Complex interrelated markets for options on common stocks have grown dramatically. Futures markets in securities and in foreign exchange have multiplied the possibilities for hedging and speculation.

Markets with similar characteristics have been a topic of interest to economists for many years. The earliest theoretical work is due to Hirshleifer (1971)[22] who showed that information commonly available before the futures markets reach equilibrium may be detrimental to overall welfare. Marshall (1974)[23] carried this line of research somewhat further. Green (1981)[24] studied futures markets which reopen repeatedly during a period of time in which new information is continually arriving. Here, in the early rounds of trading, hedging positions may offset some of the risks of price fluctuation. Green gave a set of conditions sufficient for better information to be beneficial to all hedgers. (Speculators, assumed to be risk neutral, are unaffected.)

High resolution photography in earth satellites has greatly improved the quality of crop forecasting information especially outside the U.S. The international aspects of grain trading make such knowledge directly relevant to domestic producers and users. In an interesting series of papers, Bradford and Kelejian (1977)[25] have studied the effects of these improvements on the inventory of wheat. They have estimated the benefits in both the saving of inventory costs and in the economic value of somewhat less variable spot market prices. The Bradford-Kelejian analysis does not incorporate an explicit role for futures markets, nor is it a "world-wide" model as only U.S. production is included. Extending their work in these directions would be interesting theoretically and of potentially great practical importance.

B. Information Processing in Auctions

Examining the value of information available to participants in an auction is another area where recent research has proved very fruitful. Because the rules governing most auctions are reasonably simple and well-specified and because the outcome of an auction depends crucially on the private opinions of the bidders about the objects being sold, the role of information in auctions is an interesting and tractable topic for study. To illustrate some of the issues that arise, let us consider a sealed-bid-tender auction for drilling rights on some oil-bearing property. The value of these rights depends on the amount of oil present, its cost of recovery, its quality, future prices for refined petroleum products, etc. Each of these factors is known only imperfectly by the bidders.

To a first approximation, the value of these rights to the various bidders can be regarded as equal, but the bidders are likely to have differing estimates of this value. Other things being equal, the bidder whose estimate is greatest will tender the highest bid. Consequently, even if all bidders make unbiased estimates, the winner will find that he had overestimated (on average) the value of the rights he has won. Petroleum engineers have claimed that this phenomenon, known as the *winner's curse*, is responsible for the low profits earned by oil companies on offshore tracts in the 1960's.

There are, however, countermeasures available to a bidder to ameliorate the winner's curse. First, as Wilson (1977)[26] noted, the bidder can base his bid both on his actual information and on the hypothesis that others have less encouraging information. Second, he can gather additional information to reduce the error in his estimates.

Milgrom and Weber (1981)[27] have found it useful to divide the effects of new private information into three categories. First, the information may improve the bidder's value estimate. Second, it may improve his estimate of his competitor's likely bids. Both of these effects are unequivocally beneficial to him. Third is the "competitive effect": if other bidders know that one bidder has gathered information, they may revise their bidding strategies. Relatively well-informed competitors respond by bidding more aggressively and relatively poorly-informed bidders become more cautious—the balance depends on the mix of these bidders.

The effects of public information on the outcome of an auction has also been studied by Milgrom and Weber (1980, 1981).[28] Such effects arise when the government conducts geological tests on a potential oil-bearing site and publicizes the test results. In a general model of auctions, it is shown that for three common auction mechanisms, publicizing information raises average prices.

There is much that remains to be done in auction theory. Even in the simplest auction settings, the value of information to a bidder and the effects of public information are not fully understood. Moreover, most existing analyses ignore the fact that information is used not only for preparing bids but also for making drilling decisions. As a result of that fact, secret information in the hands of losing bidders may be wasted from the public point of view. The effects of private information gathering on public welfare are in need of study.

Nearly all existing formal models of auctions focus on the case where a single object is offered for sale. In auctions for mineral rights on federally owned properties, a typical auction involves the simultaneous sale of perhaps 150 tracts. The nature of optimal bidding strategies in that setting is still not understood. Such an understanding is, of course, a prerequisite to understanding the effects that information, public and private, has on bidding behavior.

A related set of questions concerns how an oilfield is optimally explored when competitors may own the rights on adjacent fields. In this setting, one firm's exploration expenditures can directly benefit a competitor. Consequently in the auction for these properties, a firm may choose to place high bids on several adjacent tracts to get full value from its exploration activities or it may choose to place scattered high bids, in an attempt to benefit from the exploration done by others.

Another kind of auction of great practical significance occurs daily on our large securities exchanges, where buyers and sellers make offers and bids and trade securities. It is widely believed that privately held information somehow comes to be reflected in securities prices. It seems likely that a detailed model of this process would be helpful in revising the trading rules of the securities exchanges, rewriting disclosure laws, understanding the effects of insider trading, studying corporate financial structure decisions, and analyzing how well the market performs its function of funneling capital to its most productive uses.

C. The Value of Information in Games

Finally we come to the question of the value of information in two-person games. The games most widely studied arise in what is known as principal-agent problems. An individual facing a statistical decision problem, the principal, delegates the choice of his action to a better-informed player: the agent. The agent does not have the same payoff. One possible way to improve the result is for the principal to limit the action to a certain subset of possibilities.

In this context, Green and Stokey (1980a,b)[29], [30] have shown that if the informational improvement is the reduction in the probability of a totally uninformative observation, and an equiproportionate increase in the probabilities of all other observations, then the principal's welfare necessarily improves. For the agent, no informational improvement can guarantee a welfare increase, even if the two players have identical payoffs and differ only in their prior probabilistic beliefs.

Crawford and Sobel (1981)[31] have asked the converse question: When does a more similar pair of objective functions induce a higher degree of fidelity in the equilibrium transmission of information?

This line of research is obviously in only its formative stages. The hope is that one can develop a theory of the potential welfare effects of improved information to players in a game and, in this way, discover whether the appropriate incentives for information gathering and dissemination exist. If a player might lose from acquiring more information, he cannot be expected to invest in such acquisition. Prospectively, therefore, the organization of communication and control might be so arranged as to provide the right incentives, from the group's point of view, to the members whose access to new information would be of the greatest value.

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