

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 information 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. Radner¹ (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

*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.

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. Lerner² (1937) (1946), O. Lange 1942³, 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

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 economics 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.

Futia⁶ has studied complexity of decision rules in an economic setting using the algebraic theory of sequential machines particularly the Kron-Rhodes Theorem. Mount and Reiter⁷ have used an approach combining the "neural network" model of McCullough and Pitts⁸ 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 sug-

gestive 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 Phillips¹⁵ 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) Futia¹⁹ 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 Blackwell²⁰ (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 over-estimated (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.

References

1. J. Marschak and R. Radner (1972), *Economic Theory of Teams*, Cowles Foundation, Yale University, New Haven.
2. A. P. Lerner (1937), "Statics and Dynamics in Socialist Economies," *Econometrica*, 43, 1-29.
 ——— (1946), *The Economics of Control*, Macmillan, New York.
3. O. Lange (1942), "The Foundations of Welfare Economics," *Econometrica*, 10, 215-228.
4. K. J. Arrow (1951), "An Extension of the Basic Theorems of Classical Welfare Economics," Proceedings of the Second Berkeley Symposium on Mathematical Statistics and Probability, University of California Press, Berkeley, CA.
5. T. C. Koopmans (1951), "Activity Analysis of Production and Allocation," Cowles Foundation monograph, Wiley, New York.
 ——— (1957), *Three Essays on the State of Economic Science*, McGraw-Hill, New York.
6. C. Futia (1977), "The Complexity of Economic Decision Rules," *Journal of Mathematical Economics*, 4, 289-299.
7. K. Mount and S. Reiter (1974), "The Informational Size of Message Spaces," *Journal of Economic Theory*, 8, 161-191.
8. W. S. McCullough and W. Pitts (1947), "How We Know Universals," *Bulletin of Mathematical Biophysics*, 9, 127-147.
9. See T. Marschak "Organization Design" in K. J. Arrow and M. Intriligator, eds., *Handbook of Mathematical Economics*, North-Holland, Amsterdam.
10. For example, see A. Marget, "Morgenstern on the Methodology of Economic Forecasting," *Journal of Political Economy*, June 1929.
11. F. A. Von Hayek, "The Use of Knowledge in Society," *American Economic Review*, 1945.
12. S. Grossman, "Rational Expectations and the Allocation of Resources under Asymmetric Information: A Survey," Center for Analytic Research in Economics and the Social Sciences, Working paper #79-18, University of Pennsylvania.
13. J. Green, "The Non-Existence of Informational Equilibria," *Review of Economic Studies*, Vol. 44, and D. Kreps, "A Note on Fulfilled Expectations Equilibria," *Journal of Economic Theory*, 1977.
14. J. S. Jordan, "Allocation and Prediction in Stochastic Environments: An Elementary Theory" and references therein, Center for Economic Research, Discussion Paper #139, University of Minnesota. See Jordan, op. cit., Section 5; and R. Radner, "Equilibrium under Uncertainty," Section 6.4 and references therein, in Arrow and Intriligator (ed.), *Handbook of Mathematical Economics*, Vol. II, North-Holland Publishing Company, forthcoming.
15. A. W. Phillips (1958), "The Relation Between Unemployment and the Rate of Change of Money Wage Rates in the United Kingdom," *Economica*, 25, 283-299.
16. R. E. Lucas (1972), "Expectations and the Neutrality of Money," *Journal of Economic Theory*, 4, 103-124.
17. T. J. Sargent and N. Wallace (1975), "Rational Expectations, the Optimal Monetary Instrument and the Optimal Money Supply Rule," *Journal of Political Economy*, 83, 241-254.

18. L. Weiss (1980), "The Role for Active Monetary Policy In a Rational Expectations Model," *Journal of Political Economy*, 88, 221-233.
19. C. Futia (1980), "Stochastic Business Cycles," mimeographed, Bell Laboratories.
20. D. Blackwell (1951), "Comparison of Experiments," in J. Neymann (ed.), *Proceedings of the Second Berkeley Symposium on Mathematical Statistics and Probability*, University of California Press, Berkeley, CA, 93-102.
21. H. Bohnenblust, L. Shapley and S. Sherman (1949), "Reconnaissance in Game Theory," RM-208, Rand Corporation, Santa Monica, California.
22. J. Hirshleifer (1971), "The Private and Social Value of Information and the Reward to Inventive Activity," *American Economic Review*, 61, 561-574.
23. J. M. Marshall (1974), "Private Incentives and Public Information," *American Economic Review*, 64, 373-390.
24. J. Green (1981), "Value of Information with Sequential Futures Markets," *Econometrica*, 49, 335-358.
25. D. Bradford and H. Kelejian (1977), "The Value of Information for Crop Forecasting with Bayesian Speculators: Theory and Empirical Results," *Bell Journal of Economics*, 9, Spring, 123-144.
26. R. Wilson (1977), "A Bidding Model of Perfect Competition," *Review of Economic Studies*, 44, 511-518.
27. P. Milgrom and R. Weber (1981), "The Value of Information in a Sealed-Bid Auction," Center for Mathematical Studies in Economics and Management Science, Discussion Paper No. 462, Northwestern University.
28. P. Milgrom and R. Weber (1980), "A Theory of Auctions and Competitive Bidding," Center for Mathematical Studies in Economics and Management Science, Discussion Paper No. 447, Northwestern University.
29. J. Green and N. Stokey (1980a), "A Two-Person Game of Information Transmission," Harvard Institute of Economic Research, Discussion Paper No. 751.
30. J. Green and N. Stokey (1980b), "The Value of Information in the Delegation Problem," Harvard Institute of Economic Research, Discussion Paper No. 776.
31. V. P. Crawford and J. Sobel (1981), "Strategic Information Transmission," Discussion Paper No. 81-10, Department of Economics, University of California at San Diego.