CLASSIFICATORY NOTES ON THE PRODUCTION AND TRANSMISSION OF TECHNOLOGICAL KNOWLEDGE

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I. *Introduction*

Analysis of production functions over the last twelve years has suggested strongly that (*a*) a major proportion of the increase in per capita income cannot be explained by increases in the capital-labor ratio, and (*b*) production functions differ strongly among nations and indeed among regions. Since a production function is defined relative to a given body of technological knowledge, (*a*) implies that technological knowledge has been growing over time and (*b*) that technological knowledge varies over countries.

An economist could just leave the analysis at that, asserting that the causes which determine the amount of technological knowledge at any one time and place lie as much outside his province as the tastes which determine consumption patterns. But in fact, we know that significant quantities of resources are being expended by profit-making institutions on research and development. From the studies of Griliches [4] and Mansfield [8, Part IV], we know that the diffusion of technological knowledge, at least within a given economy, is partly governed by profitability considerations. Hence, it is suggested, we must regard the body of technological knowledge as the result as well as the cause of economic changes.

Economists have had a further, more detailed, preoccupation: that of the bias of technological change. A production function, if it shifts due to increased knowledge, can shift in many ways. In a two-factor model, Hicks spoke of "capital-saving" and "laborsaving" innovations and raised the question whether the bias is itself induced by economic considerations. Fellner [3] convincingly argued that factor prices, per se, should have no tendency to cause bias, since the aim of the entrepreneur is to minimize the total of costs. Kennedy [5] then sought to carry the Fellner analysis further by introducing explicitly the trade-offs between different possible biases in innovation. Kennedy, like most other current writers, has tended to replace the Hicks classification by introducing a more explicit and restricted model of technological change, namely, factor augmentation:

$$(1) \qquad Y = F[A(t)\, K,\, B(t)\, L],$$

where Y is output, K is capital, L is labor, and $A(t)$ and $B(t)$ are the total augmentations of capital and labor, respectively. Then there is postulated a "transformation function" for knowledge, in the form of a trade-off among the rates of growth of A and B and research expenditures.

Models of this type and others (e.g., Arrow [1]) have the natural motivation of using the well-tried tools of production and distribution theory in what appears to be a related field. "Knowledge," as reflected in the variables A and B, appears as an input to physical output, and we then need to supplement the ordinary production relation with an additional relation determining these newly defined inputs.

It is the suggestion of this paper that such models, though they may well be useful descriptively (however, this remains to be tested empirically), do not capture the essential features of the creation and transmission of knowledge. Technological progress is in the first instance the reduction in uncertainty. The product of a research and development effort is an observation on the world which reduces its possible range of variation. The outputs of different research projects are qualitatively different; there is no gain in acquiring the same information twice. The production of knowledge is thus basically different in character from the production of goods, where successive items can be qualitatively identical. The research and development process indeed has quantitative implications for factor productivity, particularly if it is measured at a relatively aggregated level, but these implications are a far from exhaustive description of the research and development process itself.

Research and development is thus intimately connected with the problems of uncertainty reduction which have been the objects of research in mathematical statistics and information theory. The problem of the transmission of knowledge—why different individuals and nations do not have access to equal bodies of knowledge—even more clearly requires analysis of qualitative distinctness of different items of information. Here the disciplines of information and communication theory, learning theory in psychology, and diffusion theory in sociology may be brought to bear.

The remainder of this paper will be devoted to elaborations and exemplifications of these themes. It cannot be claimed that any usable model has yet emerged, but it is hoped that the remarks here will be useful in further developments.

II. *The Production of Knowledge*

Knowledge arises from deliberate seeking, but it also arises from observations incidental on other activities. Haavelmo, Kaldor, and I (see Arrow [1] for references) have all stressed that the activities of production and investment may lead to increases in productivity without any identifiable allocation of resources to that end. An illuminating special case of increased knowledge is the discovery of natural resources. Exploration is analogous to research; but when a community is becoming settled, the members, in the course of their ordinary activities, frequently continue to make unexpected discoveries. Sutter established an agricultural community; his employee, Marshall, saw some yellow flecks in the mill race.

A more general formulation including both research and learning by doing can be formulated and will, I think, be useful. The Bayesian language will be used (for an excellent introduction, see Raiffa [11, Chaps. 1–5]); however, any sensible analysis of uncertainty will lead to equivalent formulations. Let the term "activity" be used, as usual for any process described by inputs and outputs, but we are particularly interested in the case where the outputs are not known with certainty. It can easily happen that the outcomes for different activities will be dependent random variables in the sense of a subjective probability. The case most interesting from the present point of view is that where there is an underlying unknown parameter upon which the probability distributions of outcomes for the different activities depend; then observing the outcome of one activity changes the *a posteriori* distribution of outcomes of the other. This need not happen of course; if the outcome of an activity is known with certainty a priori, then observing the outcome cannot change the probabilities of outcome of any other activity. More generally, if there is statistical independence between the outcomes of activities, the probability of distribution of the outcomes of one is unaffected by observations on the outcomes of another. Thus, if I really believe a pair of dice is fair, observing any outcome is of no use in predicting a subsequent one. But if I suspect bias and I express my suspicions by an appropriate subjective probability distribution over the possible outcomes, then observing an outcome certainly does change my subsequent expectations in accordance with Bayes's theorem.

Thus, an activity will in general have two valuable consequences: the physical outputs themselves and the change in information about other activities.

In many cases, one or the other effect predominates. The classical research situation is one in which the actual output (e.g., of nylon) is of negligible importance compared to the information gain —*a posteriori* the probability that a substance with the properties of nylon can be produced is now 1, whereas a priori it may have been a small figure. In the cases of learning by doing the opposite holds; the motivation for engaging in the activity is the physical output, but there is an additional gain, which may be relatively small, in information which reduces the cost of further production.

Once these polar cases are presented, it becomes clear that intermediate cases are possible, and in fact they not only occur but are, I would hold, frequent. In fact, the bulk of research and development expenditures are actual steps in the production process—design, engineering, tooling, and manufacturing and marketing start-up costs (see Mansfield [7, p. 106]). Each stage involves uncertainties with regard to costs and, at the end, with regard to demand. At each stage, then, something is learned with regard to the probability distribution of outcomes for future repetitions of the activity. At the same time, the physical outputs are expected to be directly valuable.

The problem of the optimal choice of a sequence of activities where both the physical outcome and the information acquired are relevant to the choice is in principle a problem of statistical decision theory, but in fact only fragmentary results have been attained. Analytically, the question is difficult, and, perhaps not surprisingly, the results that have been attained can hardly be stated simply, though definite methods of computing the optimal solutions exist. (In my judgment, this will be an increasingly common situation in economic theory; broad general theorems of the kind we admire can usually only be found under undesirably restrictive conditions. What theory can imply in a broad range of cases is a computing algorithm. To test theory, then, we need econometric evidence or at least well-informed quantitative judgments as inputs to the computing process.) Some beginnings of a microeconomic theory of research and development are found in the work of T. Marschak, Glennan and Nelson (see [10, Chaps. 1, 2 and 5]).

Building a macroeconomic theory on microeconomic foundations is not an easy task; indeed, there is not one completely successful example. But in the case of the production of knowledge, the task is apparently much harder. To proceed from an individual to a collective theory that consumption depends on income or output on inputs involves incompletely justified steps; but it is at least reasonably clear what the aggregates themselves are. Information at the individual level is describable either as the actual outcome of a particular activity or as a whole conditional distribution over states of nature, with the conditions being the actual outcomes. Such a probability distribution is hard to describe in any simple way, and aggregating this information over individuals is even harder.

Given the probabity distribution at any moment of time, individuals make production decisions. The actual outputs are not known with certainty, but one might plausibly take their expected value and regard its relation to the inputs as the production function. This will shift over time as additional information is acquired. The current models in the growth field assume (*a*) that the effect of a given body of information on the production function can be summarized in a few parameters and (*b*) that these same parameters summarize the possibilities for acquiring new information. The first assumption is undoubtedly essential if one is to get anywhere. But the second is on the face of it very misleading. Consider an economy with labor as the only factor of production and operating under constant returns to scale. Then the effect of any given information structure on the production function is completely summarized in the output-labor ratio. But a given output-labor ratio may correspond to very different information structures and therefore very different potentialities for future productivity increases. One might have been based on very thorough exploration of limited areas of investigation, with little further room for increased knowledge, while the other might have investigated more widely and have potential productivity gains available at little additional cost. Securities analysts use such considerations in their evaluations; and historical examples of this difference are frequently cited.

One might be tempted to consider as an alternative measure of aggregate knowledge Shannon's measure of information. There are of course a host of practical difficulties in applying this measure to technological knowledge. But unfortunately it does not seem to be a correct measure for either the supply or the demand side. The irrelevance of Shannon's measure to the demand price for knowledge was shown by J. Marschak [9]. To take an extreme case, consider two states of the world which are indistinguishable with regard to technology; e.g., distinguished only with regard to the number of craters on the dark side of the moon. Any discrimination between these two states would be an increase in information, but surely not one relevant to productivity. On the supply side, similarly, the cost of achieving a given increase in information may differ according to the particular observations made.

III. *Transmission of Knowledge*

The observer of the outcome of an activity can be supposed to form new probability judgments; but how does this affect the information structures of others? The transmission of the observation or of the revised probability judgments must take place over channels which have a limited capacity and are therefore costly. Though the language is borrowed from communications theory, the really limited channels are human minds, not telegraphs or printed words.

Even for the individual there is a problem of channel capacity. To transform his a priori into *a posteriori* probabilities as the result of observations which have taken time, he must remember his a priori probabilities; but memory is a channel for transmission between points of time and is notoriously limited in capacity and subject to error. Natural memory can of course be supplemented with artificial aids —books, files, computer memories—but ultimately there remains a capacity limitation. As a result, even for an individual, the transformation of probabilities and therefore the acquisition of information is less than ideal. Winter in an unpublished paper has argued that memory limitation accounts for the results of the famous Humphreys experiment which has been so crucial in modern learning theory: An event E occurs with probability $p > \frac{1}{2}$ on each of a succession of trials, with independence between trials. The individual is asked before each trial to predict whether or not E will occur; he is not told the value of p but must in effect infer it from observations. If his aim is to maximize the expected number of successes, the rational strategy would be always to predict E, at least after the process has been observed long enough to establish almost certainly that $p > 1/2$. But in fact the subjects wind up predicting sometimes E and sometimes not E, and the frequency with which E is predicted approaches very closely indeed to p. This might be explained by the assumption that they only remember a limited number of previous observations and thus never can be very well assured that it is best to predict E. (To be sure, many other explanations have been advanced in the literature.)

There have been studies by both economists and sociologists on the diffusion of innovations; the relation between the two types of studies resembles nothing so much as the parable of the blind men and the elephant. While Griliches and Mansfield stress the profitability of the investment and the risks involved, the sociologists (see, e.g., Rogers [12] and, for a more theoretical treatment, Coleman [2, Chap. 17]) are concerned with the nature of the channel connecting the adopters of an innovation with potential followers. While mass media play a major role in alerting individuals to the possibility of an innovation, it seems to be personal contact that is most relevant in leading to its adoption. Thus, the diffusion of an innovation becomes a process formally akin to the spread of an infectious disease.

There is nothing irreconcilable in the two viewpoints: in effect, the economists are studying the demand for information by potential innovators and sociologists the problems in the supply of communication channels. Different communication channels have different costs (or, equivalently, different capacities), where these costs include the ability of the sender to "code" the information and the recipient to "decode" it.

The understanding of transmission of knowledge is of especial importance in two of the key socioeconomic problems of our time: (a) international inequalities in productivity, and (b) the failure of the educational system in reducing income inequality. The two problems have a considerable formal similarity. If one nation or class has the knowledge which enables it to achieve high productivity, why is not the other acquiring that information? That a nation or class has a consistently high productivity implies a successful communication system within the nation or class, so the problem turns on the differential between costs of communication within and between classes.

(It is not intended to assert that difficulties in communication of information are necessarily the sole source of total factor productivity differences. There can be withholding of information to perpetuate monopoly positions; and both in foreign trade and in economic relations between the races, income differentials can arise from exploitation; see Krueger [6]. There might also be genetic factors. But the available evidence certainly suggests that communication problems are a major and perhaps predominant source of productivity and income differentials.)

It may be worthwhile speculating on some of the causes of these differential channel costs. Note first that all the sociological work on diffusion has put great stress on personal contact. Mass media may provide some overall alertness to change, but, except for the most alert and daring innovators, it is the example and advice of those known personally that are apparently most potent in securing acceptance of innovation. As Coleman stresses, however, personal contacts are by no means randomly distributed in the population, and the manner in which any trait (in particular, an item of information) is diffused throughout the system is correspondingly altered. To cite one case, the diffusion of use of new drugs was higher among physicians practicing in pairs than among those practicing singly.

I believe these facts cast light on the basic factors at work in the difficulties of transmission of knowledge across nations and through the educational system. Two general principles may be suggested: (1) A channel has greater capacity if the receiver regards it as more reliable; this is why personal contacts are frequently so important. (2) To a large extent, channels of communication serve purposes other than the diffusion of innovations—friendship, convenience—and the direction of diffusion may be dictated by factors in addition to profitability. Thus international channels, which typically have less other purposes to serve, are more expensive. In particular, and this may be very important, personal contacts across nations are obviously much less than within.

In amplification of (1), there is one special case of unreliability from the receiver's point of view that deserves some attention: the inability of the receiver to understand the message. As already remarked, every piece of information can be regarded as transmitted in a code and can only be used if decoded. In the first instance, a language itself is a code, and the sheer difficulty of translation perhaps can be underestimated. (The inability of English-speaking economists to learn from their French, German, and Italian colleagues is notorious.) There are problems in nonverbal forms of communication. When the British in World War II supplied us with the plans for the jet engine, it took ten months to redraw them to conform to American usage. More subtly, as several gifted observers of the educational scene have observed, there are class and racial differences in the meaning of words, not so much in the literal denotation, but in the connotations and associations, and in the significance of nonverbal behavior. In the complicated interplay of messages between teacher and student, the unreliabilities of communication can lead to extreme inefficiencies.

IV. *Exponential Growth and Stationary Bias*

To conclude, we might briefly consider two aspects of current growth models which are inconsistent with models of technological progress as information-seeking and transmitting.

One is the universal tendency to take some form of rate of growth of productivity as a variable of the system. Typically the model ends up in a quasi-stationary state with a constant rate of productivity growth. Now no known form of adaptive model, with probabilities modified by experience, leads to such a result; on the contrary, such models invariably lead to asymptotes in which output is constant. There is a limit to what can be learned even with infinitely many opportunities. Actually, with respect to the very long run, such a conclusion seems very reasonable. You cannot get something for nothing, ever, and it seems unreasonable to suppose that, by waiting a sufficient length of time, you can get any given output for arbitrarily small input. Eternal exponential technological growth is just as unreasonable as eternal exponential population growth.

But of course exponential technological growth does have the advantage of being consistent with the observed facts; if anything, the observed rate of growth of total factor productivity is increasing. I can only conjecture that, as in the case of population, the true law is something like the logistic curve, but we are still in the early phases, which resemble the exponential.

At the moment, that is, each new item of information opens up the opportunity for acquiring additional items in a constant ratio (in some sense), but eventually the scarcity of additional information will become apparent.

The other aspect is the Kennedy invention-possibility curve, the trade-off between rates of augmentation of different factors for a given research budget. In the first place, there is, of course, no warrant for assuming that technological progress is factor-augmenting; pieces of knowledge about the workings of the world need not be associated in any simple way with different factors of production. In the second place, as already remarked, in the long run, it is unlikely that rates of augmentation are the right variables to enter into any such relation. But most important, there is no warrant for the stability of the curve over time, however it is described. The curve of efficient possible innovations at any time must surely shift with the particular nature of the information acquired, a nature not summed up in productivity measures of any kind. My conjecture is that this is one place where theory should not presume to take the place of history. The set of opportunities for innovation at any one moment are determined by what the physical laws of the world really are and how much has already been learned and is therefore "accidental" from the viewpoint of economics. My guess is that economic factors have little to do with bias in technological progress (though they may have a good deal to do with its magnitude). European desire for spices in the late fifteenth century may have had a good deal to do with motivating Columbus' voyages, but the brute, though unknown, facts of geography determined what in fact was their economic results.

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