Equilibrium Diffusion of Technological Change through Multiple Processes

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ABSTRACT

This paper provides a synthesis of recent contributions to the literature of equilibrium diffusion of technological change, points out a difficulty common to all, and offers a proposal to resolve the difficulty. Diffusion can be regarded as the result of processes involving changing circumstances in an environment of heterogeneous agents. If diffusion arises from simultaneous operation of multiple processes, the ceteris paribus qualification necessary for theoretical work may be stringent; for empirical work, parameters of individual processes cannot be identified without specifying a multiple process model. But non-trivial multiple process models are generally analytically intractable. The paper's synthesis of the literature is based on a heuristic multi-process equilibrium model of the adoption decision and proposes numerical simulation as an avenue to escape the related problems of tractability and identification. A numerical experiment with a prototype multi-process simulation model suggests the possible importance of interaction among processes. Recent econometric advances offer new prospects for estimation of the parameters of such models.

EQUILIBRIUM DIFFUSION OF TECHNOLOGICAL CHANGE THROUGH MULTIPLE PROCESSES

Diffusion of technological change over a population of potential adopters is characterized by two well known stylized facts: the length of time required by the diffusion is often significant, and it varies widely among innovations.[1] Since both the inventor's reward and the innovation's impact on society are realized only as the innovation comes into use through the diffusion process, understanding diffusion is crucial to understanding the larger issues of technological change.

Empirical observation of these stylized facts and the construction of theoretical explanations has spawned a large literature. This literature is well surveyed by Feder, Just and Zilberman [15], Stoneman [70 and 71], and Thirtle and Ruttan [75]. Sigmoid time paths of aggregate adoption, notably the logistic, are prominent as statistical summaries in the theoretical as well as the empirical literature, but departures from this shape, even to the extent of temporary disadoption,[2] are not at all uncommon as empirical phenomena.

Much of the theoretical literature of equilibrium diffusion of technological change amounts to analysis of a variety of processes which have been put forward to explain the phenomenon of gradual diffusion of innovations. Two elements are common to most models of gradual diffusion of an innovation: agents are heterogeneous in some respect, and some variable relevant to the adoption decision, often exogenous to the model at hand, changes through time.[3] Many of the processes analyzed in the theoretical literature are capable of independently producing a sigmoid

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[1]Mansfield [43, p. 136]

[2]See Gold, et al. [22, p. 220] or the case of Texas in Griliches [24].

[3]David [8], as quoted in Stoneman [70, p. 97], offers a concise statement of the essence of any economic explanation of diffusion: when something changes, the optimizing behavior of heterogeneous agents leads to heterogeneity in time of reaction.

diffusion curve of variable duration, but in general, the various processes operate simultaneously and interact.[4] The theoretical implications as well as the empirical difficulties and possibilities which flow from this interaction among processes has not been widely explored.[5] The purpose of this paper is to begin the work of analysing the diffusion of innovations as the outcome of many different processes which operate simultaneously and interact to produce a wide variety of possible time paths of diffusion. The thesis of the paper is that ex ante analysis of diffusion and diffusion policy can only be accomplished by specification of a comprehensive multiple process structural model, which will probably defy analytical solution, but which offers theoretical and empirical promise through the application of recent advances in numerical techniques.

In section I, the paper illustrates three ways in which changing circumstances can lead to gradual diffusion across a heterogeneous population of potential adopters. These models are discussed briefly to acquaint the reader with the general structure of analytical models of diffusion processes, and to derive some results concerning the relationship between model structure and the widely observed empirical phenomenon of the aggregate diffusion curve. Section II assembles a catalog of processes which have been proposed to explain diffusion as an equilibrium phenomenon, and section III develops a heuristic multi-process model which provides a synthesis of the received literature. Section IV discusses the theoretical and empirical prospects of the approach, illustrating the former with an experiment using a numerical simulation which incorporates the three processes described in Section I.

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[4]Griliches [26, p. 1464] and Stoneman [72, p. 154].

[5]Some recent work on diffusion can be interpreted as extending this boundary of our knowledge, within the strictures imposed by the need to reach analytical solutions: see particularly Ireland and Stoneman [29], Stoneman and David [73], and Metcalfe [46]. The present paper offers a very broad heuristic multi-process model which allows a synthesis of received literature, provides a prototype of a numerical model which allows analysis of diffusion in a multiple process context, and suggests a theoretical and empirical research agenda along these lines.

I. Three Processes Generating Diffusion

David[6] set out the general structure underlying many models of diffusion. The components of these models are heterogeneous agents, and circumstances which change through time. This section discusses three classes of diffusion models to illustrate the nature of the interactions between the changing circumstances and heterogeneous populations which characterize the equilibrium diffusion of innovations. The section concludes with the observation that these processes generally operate simultaneously.

The three illustrative models presented propose explanations of diffusion of a single innovation in the technology of irrigated agriculture: drip irrigation.[7] Drip irrigation is an innovation which improves the efficiency with which water can be applied to crops, thereby conserving irrigation water. Drip irrigation requires that the water applied must be pressurized, which uses energy, but the smaller quantity of water per unit output needed under drip irrigation leads to reduced energy costs if the water must be raised from a significant depth.

The concepts discussed in the following models of diffusion of drip irrigation are broadly applicable; the example is chosen as a concrete illustration to facilitate exposition. The discussion of three illustrative models is not an attempt at a comprehensive taxonomy of diffusion processes, but the models do represent larger classes of diffusion processes with "isomorphic" model structure; the premise of propositions 1 through 4 is membership in the pertinent class of processes.

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[6]David [8], as quoted in Stoneman [70, p. 97].

[7]Caswell and Zilberman [5] describe the technologies and discuss the nature of the adoption decision. Fishelson and Rymon [19] discusses diffusion of drip irrigation.

A. Diffusion Driven by a Changing Threshold

Let depth of the well from which irrigation water is drawn, x, be a stochastic attribute of firms, with probability density function f(x). In each period, i, farmers make a discrete technology choice to maximize expected present value of profit, $\Pi_i(x, P(t), T)$, where P(t) is a monotonically increasing time path of energy prices, known with certainty, and T is a binary technology variable with the value 0 indicating the old technology and 1 indicating the new technology. Assume, as a consequence of drip irrigation's lower requirement of water, that the relative profitability of the innovation improves with well depth. Formally, $\Pi_i(x^0, P, 1) - \Pi_i(x^0, P, 0) < \Pi_i(x^1, P, 1) - \Pi_i(x^1, P, 0)\ \forall\ P(t)$ and $\forall\ x^1 > x^0$. Further, assume that increasing energy prices favor adoption of the innovation: $\Pi_i(x, P, 1) - \Pi_i(x, P, 0) < \Pi_j(x, P, 1) - \Pi_j(x, P, 0)\ \forall\ P(t), x, j > i$. At a given time, and for a given time path of energy prices, there is a threshold value of well depth, x^*, above which the innovation will be profitable: $\forall\ i, P(t)\ \exists\ x^* \ni x > x^* \Rightarrow \Pi_i(x, P, 1) > \Pi_i(x, P, 0)$. It follows that $x^*(t)$ is a decreasing function of time; as energy prices rise, the innovation will become profitable for shallower wells.

At a given time, t, aggregate adoption of the innovation, D, is approximated by the proportion of farms whose well depth is greater than the threshold for that period: $D = \int_{x^*}^{\infty} f(x)dx$. The conventional diffusion curve is simply aggregate adoption, viewed as a phenomenon that occurs through time: $D(t) = \int_{x^*(t)}^{\infty} f(x)dx$. Figure 1 illustrates the distribution of well depths, the declining threshold value of well depth, and the area which represents the proportion of adopters at a given time.

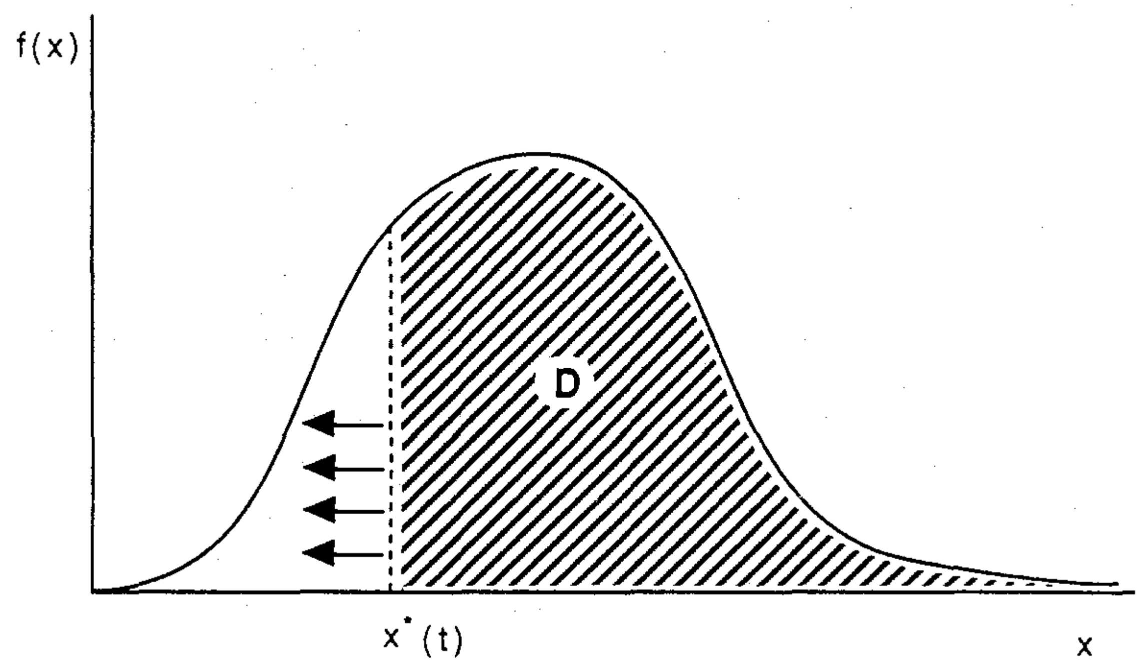

Figure 1. Changing Threshold Driven Diffusion

With the passage of time, the threshold value moves through the distribution of well depth, accumulating adopters of the innovation. If a process such as this is at work in generating gradual diffusion of an innovation, there should be no surprise that cumulative distribution functions have proven convenient functional forms for describing the time path of diffusion; both arise from integration over a a density function from one limit to some intermediate point. The shape of the resulting diffusion curve obviously depends on the dispersion of the relevant attribute over the population of potential adopters, and the time rate of change of the threshold value of the attribute. The following two propositions concern this relationship.

Proposition 1: In diffusion driven by a changing adoption threshold, the rate of diffusion of an innovation varies directly with the rate of change of the adoption threshold and the density of the population of potential adopters at the threshold value.

Proof: If f(x) is continuous and $x^*(t)$ is differentiable, then by Leibniz rule, $\frac{\partial D}{\partial t} = -f(x^*)\frac{dx^*}{dt}$.

In the absence of continuity of f(x) or differentiability of $x^*(t)$, the rate of diffusion must be defined in discrete time and the result follows from a similar argument in finite differences.

Proposition 2: The time path of changing threshold diffusion will be sigmoid under suitable specification of f(x) and $x^*(t)$.

Proof: The diffusion curve will have a sigmoid shape if the diffusion measure first rises at an increasing rate and ultimately rises at a decreasing rate. That is, $\frac{\partial^2 D}{\partial t^2} > 0 \; \forall \; t \leq \hat{t}$ and $\frac{\partial^2 D}{\partial t^2} < 0 \; \forall \; t > \hat{t}$, where $\frac{\partial^2 D}{\partial t^2} = -\left\{ \frac{df(x)}{dx}\frac{dx^*}{dt} + f(x)\frac{d^2x^*}{dt} \right\}$. It should be obvious that a wide range of specifications could produce this pattern. Two simple alternatives are provided. Let the distribution of x be uniform between a and b, $f(x) = \frac{1}{b-a}$ for x in [a, b] and zero elsewhere. A time path of x* which will generate sigmoid diffusion is $x^*(t) = b - \frac{b-a}{1 + e^{\alpha(\hat{t}-t)}}$. Another simple possibility uses linear change: $x^*(t) = b - \alpha t$. In this case, the sign of the curvature of the diffusion curve is determined by the sign of the slope of the density function, and diffusion will be sigmoid for any density function that rises and then falls in [0, b].

Specification of f(x), P(t) and $\Pi_i(x, P, T)$ implies a specific diffusion curve D(t). If a specific functional form is desired for D(t), it will "follow" from a suitable choice of f(x) and $x^*(t)$, or, perhaps somewhat more strenuously, from f(x) and the more fundamental P(t) and $\Pi_i(x, P, T)$. Extension of the decision framework to uncertain expectations of future prices and maximization of utility rather than profit is conceptually straightforward, but diminishes the likelihood of deriving analytical closed forms for the diffusion curve.

B. Diffusion Driven by Changing Attributes of Firms

Assume that energy prices are constant, so that $P(t) = p' \;\forall\; t$, and again $P(t)$ is known with certainty. Suppose now that the aquifer which supplies irrigation water is being depleted, so that well depths are increasing through time. Well depth continues to be dispersed across the population of irrigators, but the distribution moves to the right through time, as shown in figure 2. The threshold value of well depth is now constant, given constant future energy prices, and the diffusion curve is given by $D(t) = \int_{x^*}^{\infty} f(x, t)dx$.

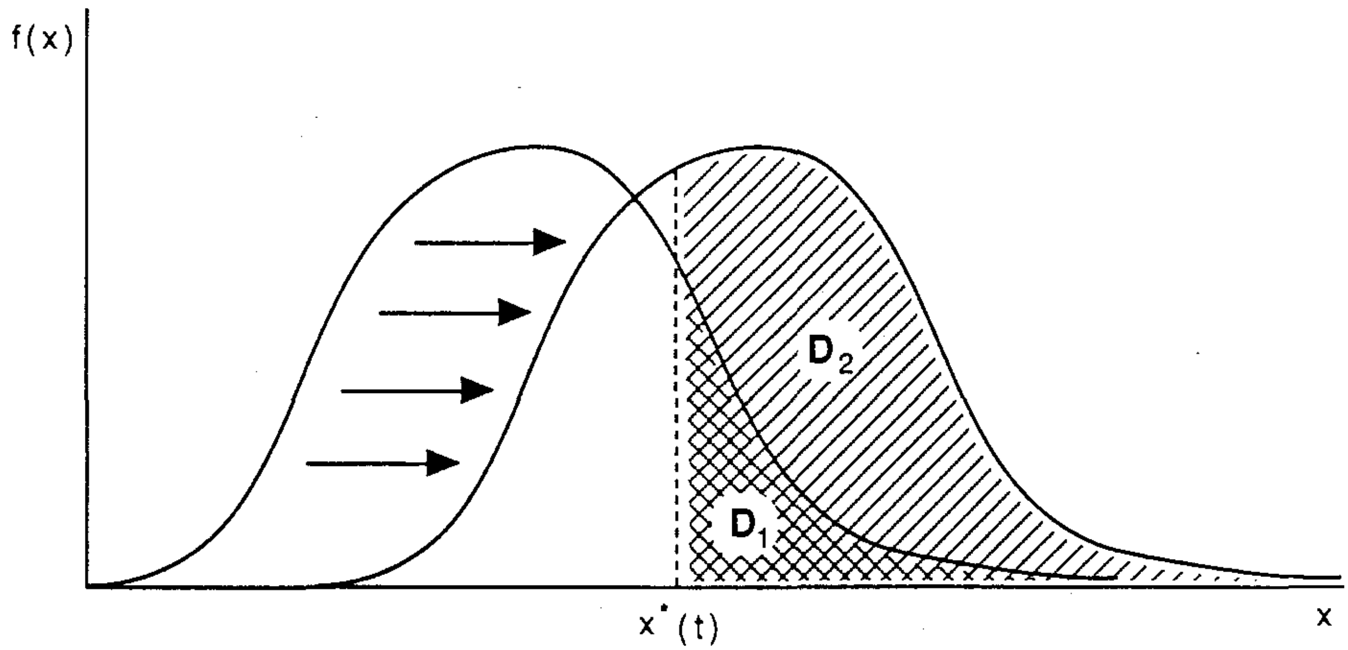

Figure 2. Diffusion Driven by Changing Attributes of Firms

In general, the rate of depletion of the aquifer would depend on the progress of diffusion of drip irrigation, contrary to the simpler exogenous depletion case depicted here. In any case, gradual change in the distribution of attributes relevant to the adoption decision can lead to gradual diffusion of an innovation, and the rate of diffusion will be related to the distribution and time rate of change of attributes.

Proposition 3: In diffusion driven by changing attributes of potential adopters, the rate of diffusion at any time is determined by the nature of change occurring in the distribution of relevant attributes. Some specifications of this change will generate sigmoid diffusion.

Proof: The first part of this proposition follows immediately from the specification of the process. The rate of diffusion generated by this process is given by $\frac{\partial D}{\partial t} = -\frac{\partial F(x^*, t)}{\partial t}$, where $F(x^*, t)$ is the cumulative distribution function for the relevant attribute evaluated at the (constant) value of the threshold, and time t. To demonstrate the possibility of sigmoid diffusion arising from this process, let $F(x, t) = G(x - t)$; then $\frac{\partial F(x^*, t)}{\partial t} = -g(x^* - t)$, and $\frac{\partial D}{\partial t} = g(x^* - t)$, where $g(\bullet)$ is the density function for G. Diffusion will be sigmoid whenever G is sigmoid.

C. Diffusion Driven by Learning

Suppose that future energy prices will remain stable at the present level, that all farms have the same well depth for irrigation water, and that the level of ground water in the aquifer is stable. Suppose that drip irrigation is a recent innovation with cost characteristics which make it immediately profitable for all farms in the population under study, but farmers are uncertain of the true cost characteristics of the innovation, and that until some experience is gained, farmers' expectations reflect caution (are generally high). Farmers are heterogeneous in their expectations, and the distribution of prior estimates of the cost parameter c is characterized by the density function f(c,t). As time passes the distribution of estimates of the cost parameter approaches the true value; the mean of the distribution approaches $\overline{C}$ and its variance approaches 0. Let c* be the critical value of the innovation's cost parameter, so that any farmer whose prior expectation for c exceeds c* will not adopt the innovation, and that any farmer whose prior expectation for c falls below c* will adopt the innovation. Note that specification of f(c,t) implies a model of learning, and specification of c* implies a model of the firm's decision-making under uncertainty. As is shown in figure 3, the innovation diffuses across the population of originally skeptical farmers in a gradual fashion determined by the original shape and evolution of expectations regarding the innovation's cost parameter, and the relationship between the true value of the cost parameter and the value of the cost parameter which is critical for the adoption decision.

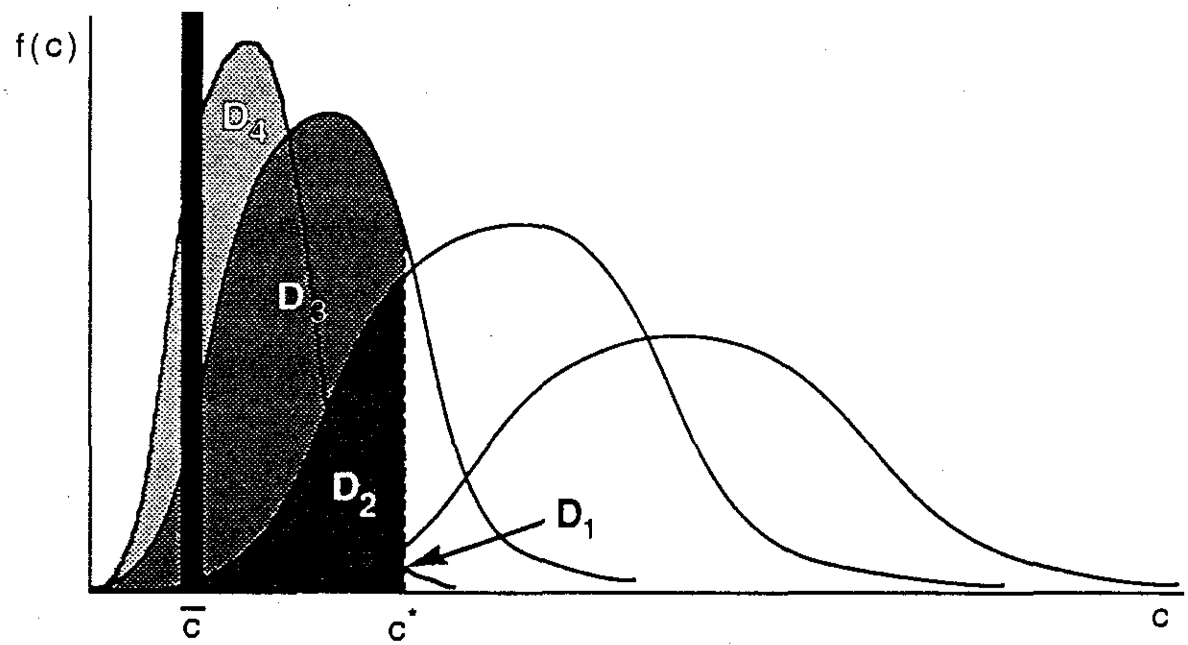

Figure 3. Diffusion Driven by Learning

Proposition 4: Diffusion driven by learning can follow a sigmoid path.

Proof: The diffusion curve is given by $D(t) = F(c^*, t)$. The demonstration requires a specification of $F(c^*, t)$ which is sigmoid in t. Let $c = \bar{c} + \frac{x}{t}$, where the random variable x has cumulative distribution function G(x). Then,

$$F(c^*, t) = \text{Prob}\left(\bar{c} + \frac{x}{t} \leq c^*\right)$$
$$= \text{Prob}\left(x \leq (c^* - \bar{c})t\right)$$
$$= G((c^* - \bar{c})t) \ .$$

Thus, $\frac{d^2D}{dt^2} = (c - \bar{c})^2 g'((c - \bar{c})t)$, and diffusion will be sigmoid if the appropriate portion of G is sigmoid.

D. Simultaneity of Diffusion Processes

Each of the processes described above is sufficient to provide a theoretical explanation of the major empirical phenomenon of diffusion: a sigmoid time path of diffusion with variable duration. Indeed, as shown above, it is generally easy to specify heterogeneity in the population of potential adopters and a time path of changing circumstances in such a way as to generate the desired diffusion curve. In general, however, all three processes should be expected to contribute to any given diffusion episode.

Specification of the individual processes is an important first step toward understanding diffusion, but in general, models which rely on a single process will only tell part of the story. At best, such models will make ceteris paribus assumptions concerning the excluded processes in order to examine partial effects which can be isolated from the more complex diffusion phenomenon in a useful way. There is, however, the danger that reliance on a model of diffusion which emphasizes one process to the exclusion of other likely contributing processes will amount to mis-specification of the model, and create more confusion than understanding. Stoneman [72, p. 166] expresses an appreciation for this danger: "We have considered a number of analytical frameworks separately. When the real world has a combination of forces driving the diffusion process it could well be that in policy terms these forces counteract each other." Griliches [26, p. 1464], after mentioning the three processes of learning by doing, aging of capital embodying the old technology, and learning about the attributes of the new technology,[8] observes that "[T]he relative importance of these forces varies from technology to technology and the optimal mode of analysis is likely to be quite sensitive to that and to the kinds of data available to the analyst."

Thus, the simultaneity of operation of multiple processes has been noted, but work in the area has been severely limited by the constraint of analytical tractability.[9] Depending on the purpose of the model being constructed, comprehensiveness and careful specification of interactions among processes can be crucial for the purpose at hand. If it is desired to reach a "sufficiency result," that a particular process can provide a plausible explanation of an observed empirical regularity, a single process model may be appropriate. If it is desired to go on to analyze the impact of instruments of public policy, or to understand the cause and effect relationships of a diffusion episode, a comprehensive enumeration of significant processes is necessary even to state the ceteris paribus conditions on which further analysis must rely.

While much useful work has shown the sufficiency of various processes to explain diffusion, the ultimate tasks of analysis in the economics of diffusion are to sort out the contributions of the various processes at work in historical diffusion episodes, and to work out the ramifications of changes in instruments of public policy or other exogenous variables. The conventional estimation of a logistic time trend of aggregate adoption and subsequent search for correlates of the slope of that trend fails to accomplish these tasks for two reasons: First, each innovation is, by definition, a departure from the historical trend. As such, forecasting the prospects for an innovation is a textbook instance of the inadequacy of extrapolation from established trends[10] and consequently, calls for careful theoretical reasoning. Second, the evaluation of the likely consequences of public

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[8]Each of these processes is discussed in some detail below.

[9]See note 5 above for pioneering efforts to incorporate multiple processes in analytical models.

[10]Gold, et al. [22] note that "adoption rates during the first few years are often unreliable guides to estimating either subsequent adoption rates or ultimate levels of application."

intervention in a process requires an understanding of the structure of the process which cannot be attained by examination of reduced forms. These tasks require a relatively rich structural model of diffusion such as the one specified below.

II. A Catalog of Diffusion Processes

The three diffusion models discussed in the previous section illustrate analytical similarities between very different processes which involve adoption of an innovation by agents who are heterogeneous in some significant respect. The present section develops a catalog of such processes capable of generating gradual diffusion. For each process, discussion will indicate sources of heterogeneity in the population of adopters, and sources of change through time. No attempt is made to survey results; the objective is merely to produce a catalog of processes which have been suggested as potentially significant in generating or altering the diffusion of innovations.

A. Contagion

The most widely cited rationale for using a sigmoid diffusion curve rests on specification of a differential equation for the time path of diffusion which includes the proportion of adoption at a given time as an explanatory variable for the rate of diffusion at that time. Appropriate specification of such a differential equation will have the logistic functional form as a solution.[11] Such a specification can either be a convenient aggregate formalization of the "bandwagon" or "snowball" effect,[12] or can arise from likening the diffusion of an innovation to a process such as

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[11]See Mansfield [42, 747-8].

[12]See Mansfield [42] footnotes 7,8 and 9 and accompanying text. For the present purposes, the "micro" justifications for the "macro" specification are of greater interest than the specification itself.

the spread of a contagious disease.[13] In either case, such an aggregate specification is best regarded as a "summary device, perhaps somewhat more sophisticated than a simple average, but which should be treated in the same spirit."[14] As such, it should be recognized that the aggregate diffusion curve is a reduced form characterization of some unspecified underlying model. The sources of heterogeneity and change through time are not specified, but many of those discussed below would suffice. It is the primary thesis of this paper that estimation of the parameters of an aggregate reduced form will be of little use in understanding the processes which explain differences among diffusion episodes for different innovations in different populations; and that a detailed understanding of these underlying processes is essential to the problem of forecasting the diffusion path of an innovation over a given population.

B. Acquisition of Information and Learning

The adoption of an innovation presupposes knowledge of the innovation's existence and at least some knowledge of its attributes. For an agent to have knowledge on which to act, information regarding the innovation must have been received by the agent, and the information must have been incorporated in the agent's beliefs regarding the innovation. The process of altering initial beliefs about the attributes of an innovation thus involves the communication of information, and the assimilation of information, or learning. There have been many suggestions that communication and learning are important processes generating gradual diffusion of an innovation.

The analogy between diffusion and spread of a contagious (communicative) disease can be regarded as a model of the spread of information about an innovation. In this model, change

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[13]See Davies [9] or Brown [3] for a good account of assumptions underlying formal epidemiological models of contagion.

[14]Griliches [24, p. 503]. In a slightly different context, Arrow [1] provides a more pointed statement: "From a quantitative, empirical point of view, we are left with time as an explanatory variable. Now trend projections, however necessary they may be in practice, are basically a confession of ignorance ... ."

through time comes from the changing likelihood of contact with a source of information (a prior adopter), and heterogeneity comes from the distribution of potential adopters over geographic space, or the distribution of some other attribute which determines the likelihood of exposure to information in a given period. The process of communication of information will be conditioned by the nature of the innovation; the extent of advertising; government efforts to communicate the attributes of the innovation through, for example, agricultural extension; the social structure of the community of potential adopters; and characteristics of the society's communications infrastructure such as the telephone network and the television broadcasting system.

Communication of information does not necessarily imply alteration of the agent's prior beliefs regarding attributes of the innovation. Altering prior beliefs on the basis of new information is one of several sorts of learning which can be important in diffusion of an innovation[15]. Communication of information and the revision of prior beliefs are closely related processes; for example, learning on the basis of new information may depend on the channel through which the information was communicated.[16] Nevertheless, it is useful for the purpose at hand to distinguish between the two because independent information can be (and often is) gathered concerning the two processes. It is very different to determine what information has been available to a potential adopter than to ascertain beliefs as to the true operating cost or useful life of capital equipment embodying the innovation.

In a model of diffusion based on learning regarding attributes of an innovation, change through time comes from beliefs gradually approaching true values of attributes, either through a simple adaptive expectations mechanism, through a Bayesian revision of prior beliefs in light of new

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[15]Two additional types of learning process are discussed in the following section, but a learning process could overlay any of the sources of change through time. Thus, "declining price of complements to an innovation" could become "growing knowledge of declining price of complements".

[16]See Brown [4] for a discussion of channels of communications.

experience,[17] or through some other specification of the learning mechanism. Whether the individual's adoption variable is discrete or continuous, a continuous aggregate diffusion curve will be approached if there is a large number of heterogeneous potential adopters, with the source of heterogeneity following a continuous rather than discrete distribution. Heterogeneity could come from within the learning process or from any other factor that affects the adoption decision. Within the learning process, it is often argued that the efficiency of allocative decisions is affected by human capital,[18] and it is reasonable to expect many populations to be heterogeneous in human capital attributes. Even in the absence of heterogeneity with respect to the information acquisition and learning processes, gradual diffusion may still result. This will be the case if learning drives unanimous beliefs about an attribute of the innovation through the domain of a distribution of critical values for that belief which reflect adoption thresholds differing according to some heterogeneous attribute of potential adopters.

Another way in which information acquisition and learning may be related (perhaps inextricably intertwined) arises when agents actively search for information.[19] In this case the potential adopter's search for information is conditioned by the value of learning anticipated to flow from the new information. Such endogenous search for information clearly does occur, and may be crucial to understanding some diffusion episodes, especially where small scale experimentation with the innovation is possible.

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[17]Lindner et al [40], Stoneman [69], and Feder and O'Mara [17] provide explicitly Bayesian models of learning.

[18]Huffman [28], Wozniak [76], Feder and O'Mara [17], Feder and Slade [18], Kislev and Shchori-Bachrach [34], Rahm and Huffman [55].

[19]Feder and Slade [18]

C. Learning by Doing and by Using

When an innovation is embodied in capital equipment, the price and quality of the equipment will obviously be important determinants of the attractiveness of the innovation. At the beginning of the diffusion process, the manufacturer of the equipment embodying the innovation may have little experience in producing the equipment. Learning by doing is learning through experience in manufacturing the equipment embodying an innovation. This learning is manifested in lower cost of production and/or improved quality of the equipment.[20]

The adopter of an innovation can also learn to use the new technology to better effect.[21] Learning by using denotes improvement in the cost attributes or productivity of an innovation through experience gained by adopters. This learning may be embodied in the specific adopter's human capital, and thus not easily transferable to other adopters of the innovation, or it may be easily transferred through, for example, instructions provided by the manufacturer of the equipment. Learning by using may lead to very large improvements in the profitability of an innovation. Rosenberg [62, p. 62] cites a wide range of studies in several industries arguing for the importance of the "slow and often almost invisible accretion of individually small improvements in innovations." For example, Enos [11] finds that cost reductions due to small subsequent improvements accounted for about three times as much reduction in cost as was due to the initial adoption of a major process innovation in petroleum refining.

The prospects for both learning by doing and for learning by using will vary greatly among innovations, both in the magnitude of improvements to be expected and in the time required for

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[20]Arrow [1] coined the term "learning by doing" and analyzed its implications in an aggregate setting.

[21]Rosenberg [62, Chapter 6]. Kislev and Shchori-Bachrach [34] and Fishelson and Rymon [19] are applications of the learning by using phenomenon.

these improvements to be accomplished.[22] In any case, the presence of learning, either in the manufacturing of equipment associated with an innovation or in its application, will imply that the innovation becomes more attractive over time. This source of change through time will cause gradual diffusion by making the innovation progressively more attractive, surpassing the adoption thresholds of an increasing fraction of the heterogeneous population of potential adopters.

D. Technological Expectations

Given the likelihood of improvements in an innovation subsequent to its initial availability, potential adopters' expectations of the prospects for these improvements can be an important determinant of the rate of diffusion. Thus, if significant improvements in the innovation are expected to occur in the near future, the decision to adopt will be delayed beyond the date when adoption would have been indicated in the absence of expected improvements.[23] Of course, the nature of the improvement's relationship to the initial adoption decision will be crucial; the adoption of fiber optic cable as a transmission medium for telecommunications is a case in point. Since the initial introduction of optical fiber as a transmission medium, immense improvements in capacity and cost characteristics have occurred, making the innovation more attractive for a wider range of applications. Most of these improvements have come in the photoelectronic components installed at either end of the fiber to transmit and receive messages, not in the fiber itself. The bulk of the cost in the adoption decision is installation of the fiber, and once installed, the fiber will benefit from improvements in the complementary photoelectronic equipment. In this case, the prospect of improvements over the state of the new technology at the time of adoption is likely to encourage

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[22]Davies makes a distinction between two classes of innovations: those which are relatively cheap, technologically simple and produced off site, and those which are relatively expensive, complex and custom made on site. This "group A / group B" distinction is based on differences in learning by doing in the industry supplying the innovation. see Davies [9, sec. 3.3.5, p. 49].

[23]See Balcer and Lippman [2]. Rosenberg [62, Chapter 5] provides an excellent discussion of the importance and wide ranging character of the effects of technological expectations on adoption decisions. Ireland and Stoneman [29] provide a formal treatment following Rosenberg [62, Chapter 5].

earlier adoption than would have been undertaken in the absence of expectations regarding improvements.

The most general formulation of technological expectations would be the specification of potential adopters' prior joint density functions for dates of improvements and the parameters of those improvements, including parameters to capture the range of complement/substitute relationships of improvements to the initial innovation. The problem could be very complex, but judicious specification of its important elements could improve our understanding of the nature of diffusion.

Technological expectations alter the formulation of the potential adopters' decision problem. Further, if expectations are revised with the passage of time or on the basis of experience, as in Balcer and Lippman [2], expectations of future change in the technology can be an independent source of change through time which could generate diffusion. It could occur, for example, that at the time of introduction of an innovation, there are widely held expectations of important improvements which would be more costly to add after the initial adoption. These expectations delay widespread early adoption. If expected improvements failed to materialize, diffusion would occur as hopes of improvement are abandoned with the passage of time.

E. Supply of Innovation

The price of inputs embodying an innovation should be among the most obvious considerations on which a firm's adoption decision is based. Incorporating such cost considerations should be among the highest priorities in the construction of structural models of diffusion.[24] Indeed, the concept of learning by doing in the manufacture of goods associated with the innovation, as it is

[24]High priority, perhaps, but undeniably challenging. See Griliches [24, note 4] for discussion of an unsuccessful attempt "to fit a model in which the year-to-year changes in the percentage planted to hybrid seed were to be explained by year-to-year changes in the price of corn, price of hybrid seed, the superiority of hybrids in the previous year or two, etc.". See also Griliches [26] on the limitations of 1957 vintage econometric art and computation technology.

applied in a model of diffusion, can be regarded as modelling an underlying source of change in cost characteristics of the innovation. Recent work by Stoneman and others[25] derives a variety of propositions from models which include endogenous supply sectors. This work presses firmly against the limitations of analytical tractability to address very important questions; unfortunately, the results are limited in scope by the stringency of simplifying assumptions necessary to achieve analytical solutions.[26]

Another consideration in explaining the time path of the price of goods associated with an innovation is the need for specialized capacity for manufacturing those goods. Metcalfe [45] analyzes the role of growth of capacity in the supplying industry on the diffusion of new technology. Growth of capacity is modelled as dependent on profitability of the industry supplying the equipment of the innovation, which depends on demand for the innovation at a given time; but this is precisely the diffusion we set out to understand. Thus, growth of supply is determined simultaneously with the rate of diffusion, and in general, neither process can be understood without specification of the other.

F. Related Goods

The conventional economic treatment of the demand for a product includes as important determinants the prices of related goods: substitutes and complements. Regarding diffusion as the time path of outcomes of supply and demand interactions, there is a clear role for prices of related

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[25]Notably Stoneman [71], Ireland and Stoneman [29], Stoneman and David [73], and Stoneman and Ireland [74].

[26]For example, Stoneman and David [73] is an excellent analysis of two types of diffusion policy: subsidy and information provision. The model includes two periods. The adoption decision is dichotomous. Knowledge of the innovation is dichotomous and independent of benefit from use of the innovation. Knowledge of the innovation diffuses through epidemic learning. Implications are derived for competitive and monopolistic market structures in the industry supplying the innovation. The paper provides very useful insights, but their application is obviously limited by the stringency of simplifying assumptions. Further, as Stoneman [72, p. 167] observes, while "other instruments could be interpreted in terms of subsidies or information packages, it is possible that by so doing we will be missing something".

goods. A recent example of the importance of related goods in the diffusion of an innovation is the role of software development for the diffusion prospects of a computer hardware innovation. Summing up prospects for a new brand of supercomputer, the New York Times recently quoted an industry expert to the effect that the new supercomputer's success "will depend on how many software companies convert their programs to run on the machine."[27] The interrelated agricultural innovations known as "green revolution" technology also fall into this category, with adoption decisions for high-yielding seed varieties, and related, but independent inputs closely intertwined.[28]

When a new process innovation is introduced, it usually comes into the world with an important related good to contend with from the outset: the substitute process which is intended to be replaced. And the old technology is very likely to improve in response to competition from the new substitute. Metcalfe [45, p. 357] refers to this phenomenon as the "steamship effect." Rosenberg [62, p. 115-6] discusses several old technologies which improved after introduction of an important substitute: the water wheel after introduction of the steam engine, the wooden sailing ship after introduction of the iron steamship, the steam engine after introduction of internal combustion engines and electric motors, gas lighting after introduction of electric lighting, and fossil fuel production of electricity after introduction of nuclear power. Aside from technical improvements in the old technology, the structure of the industry supplying the old technology could have an effect on the time path of prices of equipment embodying the old technology; if the pre-innovation price of the old equipment included the returns to market power in the supplying industry, there might be considerable slack which could allow a prompt price response to

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27"High Speed Computer Introduced", New York Times 18 July 1989. See also Rosenberg and Steinmueller [63, p 191].

28Feder [13] defines a complementarity concept for these interrelated innovations and analyses the impacts of diffusion policies in this context.

introduction of the innovation. Regardless of market structure, introduction of a substitute would imply a reduction in demand and price for the old technology.

G. Factor Prices and the Vintage of Old Capital

Changes in prices of factors of production used to a greater or lesser extent by different technologies is often cited as a source of change through time which drives diffusion. The example above of increasing expected price of energy inputs is an illustration. Ray [54, p. 6] mentions the low price of hydroelectric power in Scandinavia as altering the relative profitability of steelmaking technologies and causing a different pattern of diffusion than observed elsewhere. The price of labor is a source of heterogeneity in other international comparisons in Ray [54], notably the shuttleless loom, which is apparently profitable only to weavers facing a sufficiently high ratio of the price of labor to the price of capital; this ratio is distributed across potential adopters and adoption is indicated for that part of the distribution above the threshold value implied by the changing attributes of the innovation. Further, the distribution of relative prices could move across a fixed adoption threshold over time; Salter [64], David [8], and Davies [9, 10] all posit an increase in wages relative to the price of capital.

The original source for most discussions of the vintage distribution of capital equipment is Salter [64]. Salter discusses a more or less continuous evolution of best practice technology which is either new investment or replacement investment, installed when operating cost of the old equipment exceeds total cost of the new equipment. New investment is spread over a number of periods because the supply of investment funds is limited, and replacement of old equipment occurs gradually because heterogeneity of the old plants leads to dispersion in the time at which the operating cost versus total cost decision turns in favor of replacement. Change through time occurs either due to input prices growing further and further away from the vector of input prices for which a given vintage was designed, or due to physical deterioration of equipment, which Salter recognized[29] but regarded as generally negligible.

H. Scale of Operation

Scale of operation is a source of heterogeneity emphasized in several models.[30] The most obvious way in which scale of operations affects the decision to adopt a new technology is that some innovations are embodied in indivisible units of capital and require a lumpy investment which will only be justified for firms facing sufficient final demand. It should be noted that since the adoption decision considers the period from the date of the decision forward, "scale of operation" in this context refers to the firm's expected scale of operation over the relevant period, which may not coincide with recent experience. That is to say, for example, that a firm may adopt a new technology requiring lumpy investment as part of a larger expansion decision.

Another way that scale of operation enters into the adoption decision is through its role as determinant of a firm's attributes with regard to learning. If the benefit of knowledge of a new technology is a reduction in the cost per unit of manufacturing a product, such knowledge will be more valuable to a firm which produces more units of output. If firms continue the search for knowledge to the point that equates the marginal cost of search to the expected benefit of knowledge acquired, then large firms will search more and acquire more knowledge, adopting the innovation earlier. In this case, the relevant scale variable is also expected scale.

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[29]Salter [64, p. 53].

[30]David [8], for which see the discussion in Stoneman [70, p. 97 ff], Davies [9, 10], Feder and O'Mara [16], Feder [13], Feder and Slade [18], Oster [51].

I. Risk Aversion and Uncertainty

The role of risk aversion and uncertainty have long been recognized as potential explanatory factors in the diffusion of technological change. For example, Mansfield [42] mentions both.[31] There are two distinct ways in which uncertainty can enter into the adoption decision for a new technology: there can be differences between the old and new technologies' objective distributions of uncertain outcomes, and there can be a priori uncertainty about the true attributes of the new technology. Both appear in the literature[32], but the latter is by far the more commonly cited. Uncertainty concerning the true attributes of an innovation is generally assumed to be resolved with time and/or experience, and was discussed above as a learning phenomenon. It was seen to provide both a source of change through time and a source of heterogeneity in the population of potential adopters. A further source of heterogeneity arises from differences in aversion to risk. If uncertainty in one form or the other is important to an adoption decision, and some aspect of the problem is changing through time to make the innovation more attractive, heterogeneity of risk aversion parameters of potential adopters will induce a distribution of adoption dates and generate gradual diffusion.

J. Other Considerations

A variety of other considerations bear on decisions regarding adoption of an innovation. Several are collected here because they do not fit easily into any of the other groups discussed above. Some are relegated to this residual category because they are very particular to a given innovation; others are included here because they would be difficult to measure, model or anticipate. The first

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[31] Mansfield [42] note 7 on the role of uncertainty and p. 747 on heterogeneity in aversion to risk.

[32] /for a single paper which mentions both, see Feder [13, p. 95].

group is crucial to any effort to construct a quantitative model of a diffusion episode. The second group is, for now, relegated to the ceteris paribus caveat, and as such amounts to a challenge for further research.

In the category of particular considerations that are crucial to diffusion episodes to which they apply, well depth, mentioned in the illustrative models above, is an example. Well depth in this context could be regarded as a qualitative dimension of an input which bears on the decision regarding optimal irrigation technology. The work of Caswell and Zilberman [5] considers well depth, and also considers another qualitative dimension of an input, "land quality," defined in a way that is very particular to the performance of irrigation technologies. Feder [13, p. 98] mentions agroclimatic zones as a source of heterogeneity in the desirability of an innovation. Climate is obviously an important source of heterogeneity related to the diffusion of any new agricultural technology; in the event of global warming caused by the accumulation of greenhouse gases, it could also become a source of change through time, driving widespread adoption of locally new agricultural technologies. Ray [54, p. 6] notes the importance of qualitative characteristics of iron ore inputs to technological choice in steelmaking.

Generally, in order to understand a particular diffusion episode, it will be necessary to model the structure of the adoption decision, to understand the way in which the parameters of that decision model are distributed over the population of potential adopters, and to understand the way in which they change through time. This is a difficult task which implies a great deal of attention to the intricacies of particular adoption decisions; but analysis of diffusion which does not rely on these structural fundamentals cannot go far beyond a search for ad hoc statistical relationships, and while this may provide a useful "summary device," it will teach us very little that can be applied, ex ante, to another diffusion episode.

Although these considerations may be difficult to measure, model or anticipate, there are also changes, difficulties and possibilities which may arise during the course of a diffusion episode which amount almost to imponderables. For example, Falcon [12] discusses political implications which might flow from income distribution consequences of green revolution technology. Feder, Just and Zilberman [15, p. 288] mention the possibility of redistribution of landholding among groups with different propensities to adopt the new technology. Either of these effects arising in the initial part of the diffusion episode would certainly have significant implications for the remainder of the diffusion. Such consequences of a technological change may be quite remote from the first order effects of the change, but over the decades during which a major technology diffuses, it can easily happen that the political and economic environment of the adoption decision evolves jointly with the characteristics of the new technology.

K. Summary

In general, the considerations which can be expected to affect the time path of aggregate adoption include any variables which impinge on a firm's decision to adopt a new technology, the distribution of those variables over the population of potential adopters, and the rate of change of those variables through time. It is argued above that for some purposes it is desirable to model diffusion as an outcome of the simultaneous operation of multiple, interacting processes; a survey has been provided of variables which have been proposed as entering into those processes. Table 1 collects these variables together for ease of reference. The classification of effects into sources of change through time, sources of heterogeneity and other factors conditioning diffusion is convenient, but not without ambiguity; entries are not duplicated in the table, even though several could reasonably appear under more than one heading.

Table 1. Ingredients for economic models of diffusion

Sources of Change Through Time	Sources of Heterogeneity	Factors Conditioning Diffusion
Learning about attributes of innovation	Human capital	Market structure in adopting industry
Cost of equipment for innovation	Expected scale of operation	Market structure in producing industry
Learning by doing in manufacture of innovation	Initial vintage/age structure of existing equipment	Market structure in related producing industries
Learning by using innovation	Risk aversion	Information infrastructure
Cost of substitutes and complements for innovation	Innovation specific attributes: climate, land quality, well depth, ...	Endogenous improvement of old technology
Rising operating cost of old capital equipment	Access to information	Advertising and extension
Structural change		Tax/Subsidy policy
Communication		Business cycle

III. A Multi-Process Diffusion Model

The task of this section is to describe a heuristic model of diffusion which allows a synthesis of the literature mentioned above. The model is represented in graphical form in Figure 4. The intention is to erect a unifying framework which can incorporate the multitude of influences discussed in the received literature, not to elaborate in detail the many relationships required for a fully specified version of the model; a brief discussion of the prospects for the theoretical and empirical application of such a specification is offered in the remainder of the paper.

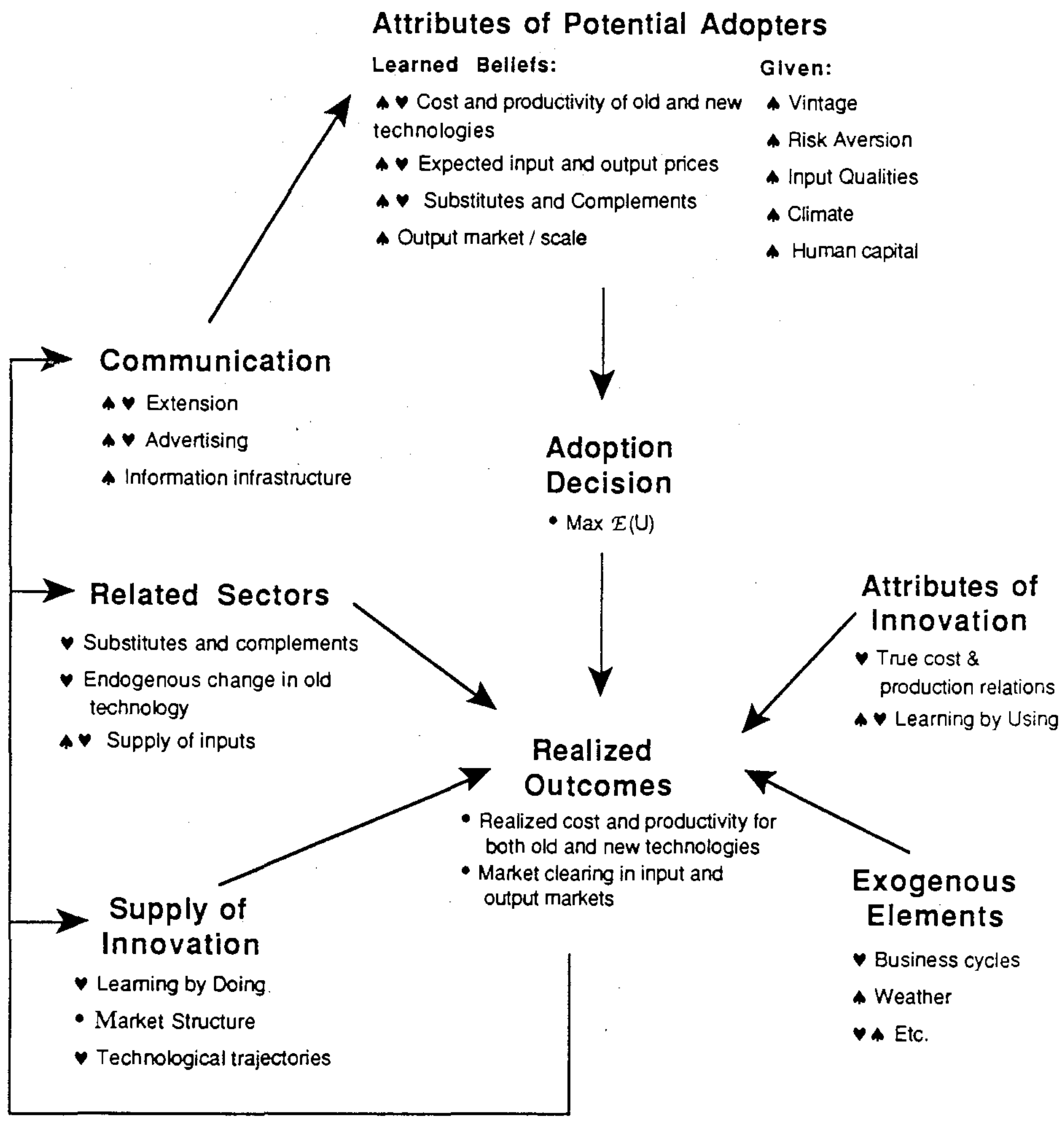

Figure 4. A Multi-process Model of Diffusion of an Innovation

Diffusion of technological change is the aggregate of individual adoption decisions regarded as a phenomenon which occurs over time. A structural model of diffusion must explain the nature of the adoption decision, show the differences among firms that lead to different outcomes of the adoption decision at a given time, and show the pattern of change through time which leads the adoption decision to come out in the affirmative for more and more firms as time passes. In Figure 4, sources of change through time are indicated by ♥ and sources of heterogeneity are indicated by ♠. Arrows indicate the direction of influence or the flow of information.

Attributes of the firm appear at the top of the figure. Learned prior beliefs are included among the firm's attributes. The revision of these beliefs on the basis of new information, experience, or the passage of time is the process of learning. The incoming arrow provides all information which is available from the history of the diffusion episode to date. Specification of the learning process amounts to indicating what information matters, and how available information is transformed into revised prior beliefs. The learning process could be specified in a variety of ways: the process could be degenerate, with initial beliefs set parametrically to their true values; it could be simple, with priors approaching their true values through a simple adaptive expectations model; or, it could be more complex, specified as Bayesian revision of priors on the basis of noisy signals observed in the form of the sequence of previous market outcomes in the presence of stochastic exogenous elements such as weather. Initial priors and the structure of the learning process (e.g., the role of human capital) provide sources of heterogeneity, and learning itself can provide change through time. Other firm attributes, not subject to learning, are inputs to the adoption decision and may vary across firms, providing a source of heterogeneity.

The adoption decision is conceived as a rule which maps a vector of firm attributes, including prior beliefs, into a production plan. Depending on the nature of the technology, and the purposes and resources of the modeling effort, the adoption decision can be characterized as a binary or a continuous variable. For a finely divisible innovation, experimentation with small scale adoption can yield information to the learning process by feedback of realized outcomes through the communications process. The model is neoclassical in the sense that it specifies an optimizing decision criterion and uses the equilibrium of supply and demand as the predicted outcome.[33]

After production plans are formulated in the adoption decision block, aggregation to the market level and realization of all random elements is accomplished under "realized outcomes." This process relies on inputs from the innovation supply sector, related sectors, the true attributes of the innovation, which may be changing through learning by using, and exogenous elements which may be stochastic, like weather. It is this process which generates information for the communications process and for subsequent decisions of the innovation supply sector and related sectors. Observation of the aggregate realized usage of the innovation, either as the fraction of firms using the innovation or the share of aggregate output produced with the innovation, generates the diffusion curve.

Information on realized outcomes is transmitted to the learning process through some channel of communication. The character and quality of this transmission of information is modeled in the communication block at the upper left of the figure. The communication process could be the degenerate case of direct and costless transmission of all outcomes symmetrically to all potential adopters, or it could entail costly transmission of signals of varying quality to potential adopters, with private observation of some information concerning a firm's outcomes. The process could

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[33]In concluding their excellent survey of the economic literature of technological change Thirtle and Ruttan [75, p.131] remark on the difficulty of explaining the phenomena of technological change within the neoclassical framework: "When time is dealt with, historical reality is often sacrificed to mathematical tractability. The failure to come to grips with historically contingent events is at odds with the reality of technical change at the micro level. Firms differ in their technological characteristics, in part because they have different histories and different past experiences." Despite the criticism, Thirtle and Ruttan decline to follow Nelson and Winter [50, p. 205] in their conclusion that the neoclassical approach has lead to a dead end. The present paper is an initial step in a research program which follows Nelson and Winter in the use of numerical rather than analytical methods to avoid the problem of tractability, but maintains a neoclassical approach to micro level decision making, with a view to extending, rather than abandoning, the analytical insights of the neoclassical tradition. Despite these attributes of the present model, no conflict is seen with models of a more behavioral nature, such as the work of Davies or Metcalfe; a wide variety of behavioral rules can be derived from an optimizing model with the appropriate information structure, and while it is plausible that a change in circumstances might lead firms to abandon a behavioral rule in favor of direct maximization, the reverse is not plausible. See Phlips' discussion of Nelson's paper in Stiglitz and Mathewson [68, p. 473].

incorporate geographic dispersion of potential adopters, and could portray the effectiveness of communications infrastructure. The communications process could be altered by a variety of government information provision policies.

IV. Directions for Future Research

It has been argued that a multi-process model is essential to understanding many of the important questions of the economics of diffusion of innovations, and the previous section offered a heuristic statement of a relatively comprehensive version of such a model. The present section discusses prospects for theoretical and empirical work with such a model.

First, it should be expected that a model of this nature of even moderate complexity would not yield interesting analytical solutions, but that with the loss of generality involved in specifying actual functional forms, numerical solution would be possible.[34] One form that numerical solution of the model could take is stochastic simulation of a diffusion episode. Such a stochastic simulation would involve generation of initial attributes of the population of potential adopters, using a specified joint distribution; solving the adoption decision problem for each potential adopter; generating random numbers from appropriately specified distributions for sources of uncertainty which are only realized after production plans have been made; determining individual and aggregate outcomes consistent with individual ex ante production plans, the plans of other sectors, and exogenous factors; communicating information from realized outcomes to the learning process, giving effect to any random elements incorporated in the communications process;

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[34]Referring to numerical solution of applied general equilibrium models, Shoven and Whalley [65] note: "The value of these computational models is that a computer removes the need to work in small dimensions: Much more detail and complexity can be incorporated than in simple analytic models."

revising attributes of potential adopters through the learning process; and iterating through successive periods until the diffusion episode is complete.

In addition to numerical solution in the mode of stochastic simulation, the model could be solved in an empirical mode, using observed attributes from a cross-section data set and historical realizations of exogenous elements to estimate parameters of the specified processes which best reproduce an actual diffusion episode. The next two sections discuss stochastic simulation with the model and the following section discusses prospects for estimating parameters of the processes by solving the model in the empirical mode.

A. Stochastic Simulation

A complete specification of the model described above could be used as a stochastic simulation for two types of application. The first involves derivation of theoretical generalizations of a fairly broad nature from numerical experiments. The second uses the model as a device for ex ante "what if" analysis for a specific innovation. These two types of application are discussed in turn, and the first type is illustrated with a discussion of an experiment using a simulation which integrates the three diffusion models applied above to drip irrigation.

Numerical experimentation with a simulation model to derive theoretical results is the method for which Nelson and Winter [50] is probably the best known representative, but which is also followed in the applied general equilibrium literature,[35] and which was used in the area of diffusion by Feder and O'Mara [16]. This method of theorizing involves the derivation of the logical consequences of a structural model by comparing numerical solutions of the model with parameters chosen for experimental purposes. Just as in the case of theorizing by means of comparing analytical solutions, numerical experimentation only derives the consequences of the

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[35]See Shoven and Whalley [65].

structural model specified. The two methods differ in the nature of the constraints on model specification imposed by the solution algorithm. For example, the structure which must be imposed on an analytical comparative statics problem amounts to restrictions on the complexity of the problem and on the signs and quantitative relationships among partial derivatives of the functions characterizing the problem; the specification of functional forms is avoided for relatively simple structures, and the specification of parameters is certainly avoided. For numerical solution, a full specification of functional forms and parameters is required, but much more complex structures can be analyzed. Generally, numerical experimentation is attractive when a relatively complex model is necessary to capture essential features of the problem, and when it is desired to incorporate available empirical knowledge of the functional forms, and especially, the parameters of some facets of the problem. For application to diffusion, numerical experimentation is desirable both because of the need to specify a relatively complex, multiple process model to capture important features of the problem, and because of the availability of empirical information on some facets of the problem.[36]

The second type of application of the model as a stochastic simulation uses the model as a device for ex ante, "what if" analysis for a specific innovation. This amounts to using the model as a logical structure which allows the incorporation of scraps of prior information of diverse origin. As a comprehensive structural model of diffusion, the framework suggests the questions which should be asked in order to forecast the course of a diffusion episode under study; it provides a structure which integrates and gives meaning to answers for those questions, where answers are forthcoming; and it allows sensitivity analysis for those parameters about which very little information may be available. Use of the framework in this context should facilitate interdisciplinary collaboration among economists, sociologists, engineers, geographers, marketing

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[36]A more through discussion of the methodological issues which arise in choosing between the alternative bundles of compromises entailed in numerical and analytical solution algorithms would be useful, but is beyond the scope of this paper. See Rausser and Johnson [56] and Johnson and Rausser [31].

experts, and industry analysts of other backgrounds. For a major innovation, a wide variety of expertise may be required to specify the structure of the important processes, to estimate the parameters indicated by that structure, and to evaluate the resulting model in terms of plausibility of outcomes, both in the aggregate, and for internal consistency.

In the absence of a comprehensive structural model of diffusion, the best that can be done for ex ante analysis is to rely on the subjective judgement of industry experts. If the literature is correct about the various influences on diffusion, such subjective judgements must consider the many elements of a comprehensive model, albeit in an informal way. Formal specification of the comprehensive model allows consistent incorporation of all available objective information, allows discussion among experts of the proper structure of the model, and allows division of labor in making the inevitable subjective judgements; it also provides a mechanism for applying the experience of one diffusion episode to the next innovation for which ex ante diffusion analysis is required.

In ex ante analysis, where some parameters must be based on subjective estimates, a simulation which integrates all available a priori information could be used as a device for generating feedback on the implications of parameter choice in the process of eliciting estimates of those parameters. In providing such feedback, care must be taken to allow reconsideration of estimates only on the basis of unanticipated consequences within the expertise of the person whose subjective estimate is being elicited. Otherwise, there would be the danger of allowing a parameter to be chosen on the basis of subjective expectations regarding aggregate outcomes, resulting in the tail effectively wagging the dog.

B. Simulated Diffusion of Drip Irrigation

In the spirit of application of the model as a stochastic simulation to derive theoretical propositions, a simple prototype has been developed to allow simultaneous operation of the three processes illustrated above in the context of diffusion of drip irrigation. The model incorporates heterogeneity in the form of a distribution of initial beliefs concerning the innovation's cost parameter and a distribution of well depths; change through time comes in the form of learning about the true cost parameter, rising expectations of future energy prices, and depletion of the aquifer. Examined individually, as in Section I, each process was seen to be sufficient to generate gradual diffusion, of the sigmoid form under some specifications. The present simulation uses very simple parameterizations of these three processes to conduct a single experiment to illustrate the possible importance of the interaction of processes. The parameter which provides the basis for the experiment -- the covariance between two sources of heterogeneity -- is only meaningful in a multi-process context.

A diffusion episode was simulated for three populations of 500 firms each. The model's two sources of heterogeneity, well depth and initial prior belief regarding the innovation's cost parameter, have identical means and variances in each population. The populations differ only in the covariance between the two sources of heterogeneity. Negative covariance indicates that low cost estimates for the new technology, or optimistic estimates of operating characteristics, are associated with deep wells. Positive covariance occurs if high cost expectations are associated with deep wells. Either association is plausible; which exists in a given population is an empirical question which can be answered by straightforward means. As is apparent from the three diffusion curves in figure 5, the difference is significant.

All three diffusion curves have the typical "S" shape. If the formation of initial prior beliefs regarding the innovation's cost parameter is independent of well depth, diffusion begins as the innovation becomes available. In the case of positive covariance (high cost expectations associated with deep wells) diffusion doesn't begin until some time has passed, but then proceeds more rapidly. With negative covariance, the most likely beneficiaries of the new technology are the most optimistic about its cost, and a larger fraction of the population adopts the technology immediately.

In this case, however, the technology diffuses much more slowly over the remainder of the population.

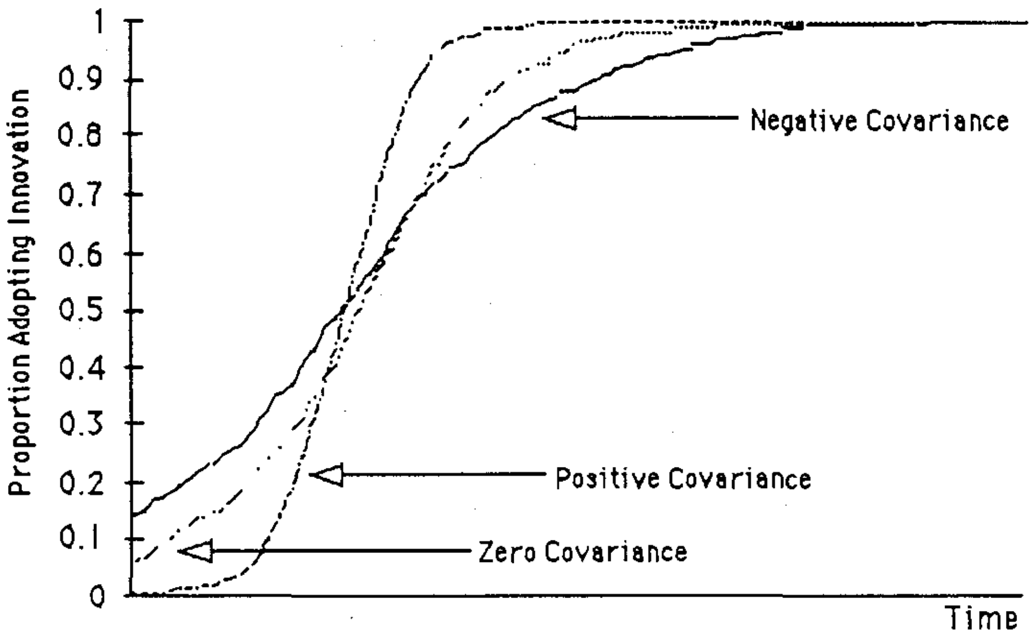

Figure 5. Diffusion curves with differing covariance between well depth and initial estimate of cost parameter of new technology

The implication to be drawn from this experiment is simply that interaction among processes can matter, with the obvious corollary that a model which incorporates only a single process may miss something important. The following section discusses the need to avoid missing anything important in empirical estimation of the parameters of a structural model.

C. Estimation of Parameters

The model described above can be solved in two different modes. The first, as an ex ante stochastic simulation, generates random numbers from a specified distribution to substitute for realizations of exogenous variables such as weather, which are unknowable before they occur.[37]

[37]One may also substitute realizations of a stochastic process for the heterogeneous attributes of potential adopters, which, in principle, are knowable before the diffusion episode. For the moment, suppose that a complete census of potential adopters' attributes is available.

The other mode of operation of the model, the empirical or historical mode, has available information, in principle, on all inputs to the model as well as outcomes such as the historical time path of diffusion, which the model is designed to predict. Once the structure of the model has been specified, and necessary data has been provided, it can be regarded as a black box which transforms a vector of parameters into a diffusion curve. If the actual, historical diffusion curve is also available, the possibility arises to choose the vector of parameters which "best" reproduce the true diffusion curve. Recent econometric work on estimators for processes which can be simulated, but for which no closed form analytical solution exists, offers the promise of estimation of parameters of a multiple process diffusion model. Detailed development of such an estimator requires a full specification of the simulation model, and neither task is undertaken here;[38] instead, a discussion is provided of the promise offered by the approach and the nature of data required for its implementation.

The best possible data from which to estimate the parameters of a structural model of diffusion would be the cross section of firm level attributes and the time series of firm level production regimes, including technology choice, over the duration of the diffusion episode under study.[39] More commonly, time series data will be available giving aggregate adoption percentages (for a diffusion study) or a cross section will be available giving firm attributes at a single time (for an adoption study). Perhaps the greatest promise of the present approach is that it allows the use of both types of data in the same model.

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[38]The simulation estimator idea was suggested by Lerman and Manski [39]. Pakes [52] developed such an approach to estimate the distribution of returns to patent holding. Pakes develops a liklihood function which can only be evaluated with the aid of numerical simulation. The liklihood function is maximized over parameter space, and the information matrix estimated by evaluating the liklihood function at nearby values of the parameters. See also Lee [37], McFadden [44], and Pakes and Pollard [53].

[39]With this very unlikely data set it might be possible to specify the estimation problem as a conventional simultaneous equations model.

Cross section data is used in concert with aggregate time series data by assuming that the distribution of attributes of the available cross section do not change over the course of the diffusion, except insofar as they change through processes included in the model. Then, attributes for periods other than that for which the cross section is available are generated internally by the simulation. Time series data is required for all other inputs to the model, such as exogenous prices of inputs or related goods, historical realizations of exogenous factors such as weather, and outcomes predicted by the model. Of course, individual outcomes (production regimes, realized profits, etc.) would be best, but such data is only very rarely available. In the alternative, the likelihood of an aggregate diffusion pattern, given a parameter vector, can be evaluated, and the parameter vector can be chosen to maximize the likelihood of observed aggregate outcomes.

It should be remarked that straightforward estimation of the entire vector of parameters of a general specification of the model would probably not be possible, or interesting. It should be expected that an unconstrained general specification would admit multiple parameter vectors which would yield nearly the same value of likelihood; the likelihood function would probably be approximately flat near the maximum. Useful parameter estimates would only be possible by the imposition of additional structure on the model, in the form of independent estimates of the parameters of some processes, or narrower specifications of some process structures as indicated by prior information other than the data at hand. For example, independent estimates of profit functions may be available for either the old or the new technologies, or both; independent information may be available on industry expectations; ex post evaluation of the changing attributes of the innovation may be possible; or marketing studies may have traced changes in potential adopters' beliefs or available information over the course of the innovation. In the absence of other information, the problem is probably far too complex to hope to estimate a comprehensive structural model.

Another promise offered by the approach is the estimation of parameters of a structural model of diffusion from data on multiple innovations. Many of the most interesting diffusion studies have considered more than a single innovation; indeed, identification of the correlates of the structural parameters in attributes of the population and attributes of the innovation is the ultimate goal of policy oriented diffusion research. Conceptually, this could be accomplished if some components of the model are specified as structurally the same for diverse innovations. For example, if the communications process depends on attributes of the population of potential adopters, and the attributes of the information being communicated, but not on the identity of the adopters or the innovation, then the parameters of those processes could be estimated from data covering multiple diffusion episodes. Thus, a simulation model for innovation A could be extended to cover innovations B and C by specifying new structures for the innovation-dependent processes. Diffusion curves for all three innovations would be a joint outcome of the simulation model, and all structural parameters which are independent of the identity of the innovation could be estimated from data on all three innovations, benefitting from the larger number of observations and the greater variation of the combined data set. The communication and learning processes are obvious candidates for innovation independent processes; at the other end of the spectrum, the structure of the adoption decision will be innovation specific except perhaps for very closely related innovations.

V. Conclusion

The diffusion of an innovation over a population of heterogeneous potential adopters is a complex phenomenon, potentially influenced by a great variety of processes which are set in motion by the introduction of the innovation. This paper has argued that elaboration of a structural model of these simultaneously operating processes is essential to understanding the diffusion of technological change. This is true both for the theoretical and the empirical sense of the word "understanding." The common practice of specifying a reduced form equation for an unspecified structural model offers no theoretical explanation of the diffusion phenomenon. Specification of a single process structural model offers a perfectly satisfactory explanation, except that there is a myriad of such processes that have been suggested in the literature, and they are widely recognized to operate simultaneously. Thus, a structural model which does not encompass the important processes of a particular diffusion episode will not provide a reliable guide, and theoretical results from such a model are best regarded as "partial" results, subject to a ceteris paribus restriction which may be very stringent. The need for a theoretical explanation rather than merely a historical "summary device" is crucial to the policy analyst, whose work is necessarily ex ante -- before there is any history to summarize. In the empirical sense of "understanding," a comprehensive structural model is needed to allow estimation of parameters of processes which operate simultaneously and interact. A partial model which misses the influence of important processes will lead to empirical work which says nothing of omitted processes and gives biased estimates of the parameters included.

The prospects for both the theoretical and the empirical analysis of diffusion in a comprehensive framework have been greatly advanced by recent changes in the technology of econometrics and computation. The approach suggested above would not be interesting if it were not possible to solve the model and to estimate its parameters; both are possible through the technique of numerical simulation, with significant limitations in both cases. Further methodological work would be desirable on the compromises entailed by the alternative approaches to solution, and the implications each holds for problem formulation.

The word "innovation" suggests that ex ante analysis of each diffusion episode will present a problem of a novel structure, with very little of relevance which can be learned from previous episodes. The heuristic model developed above offers a "meta-structure" which allows analysis of sources of regularity among diffusion episodes, while respecting the novelty of the structure and circumstances of each innovation's adoption decision. Elaboration of such a comprehensive framework decomposes the analytical problem into process models, some of which may be unique to the innovation under study, but some of which are likely to have a structure that is shared by prior diffusion episodes. When this is the case, parameters could be estimated from historical diffusion episodes to provide useful prior information for the analysis of new innovations.

For theoretical purposes, the framework allows loosening the constraint of analytical tractability, which is important for multiple process models, at the cost of the imposition of a specific parameterization. Application of the framework to the study of historical diffusion episodes offers the promise of using available data to estimate parameters of a comprehensive structural model, with the possibility of incorporating data on multiple innovations to estimate the parameters of common processes. The "meta-structure" provided by the framework organizes the research necessary for ex ante analysis of a new innovation, and provides a formal structure which allows the accumulation of knowledge from one diffusion episode to the next.

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