Technological Diffusion : The Viewpoint of Economic Theory

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I. Introduction

Technological diffusion is the process by which innovations (be they new products, new processes or new management methods) spread within and across economies. Some understanding of the process of technological diffusion is essential if we are to gain any insight into processes of economic growth and development, for, whatever the emphasis has been in the past in research and public policy, it is the application of innovations (diffusion) rather than the generation of innovations (invention or R & D) that leads to the realisation of benefits from technological advance.

My intention in this paper, which is my third attempt at surveying this subject (see Stoneman 1983(a), 1983(b)), is to consider the different approaches in the economics literature that have been pursued in order to rationalise certain "stylized facts" that describe the diffusion process. The two "stylized facts" most commonly noted are the following.

(i) The spread of the use and/or ownership of a new technology is a time intensive process (see for example Mansfield (1968)).

(ii) In many cases, plotting usage or ownership of a new technology against time yields an S shaped (or sigmoid or ogive) curve (see for example, Griliches (1957) or Davies (1979)).

The economics literature on diffusion has grown apace over the last twenty years. To make my task manageable I am restricting myself to the theoretical underpinnings of this literature. Much of the published work represents implicit or explicit applications of theory to particular case studies. I do not wish to belittle this work, it is most important that our theories should be tested. Here, however, I am more concerned with underlying rationales than observations of outcomes. I will be restricting myself to the economics literature, although other subject areas have interesting points to make on diffusion. We might however note that parallels between the work in sociology, see Rogers (1983) and geography see Brown (1981), and the work in economics are surprisingly frequent.

The spread of a new technology occurs in a number of dimensions. The potential buyers of a technology can be corporations, public institutions (which two I generally class together as firms) or households. The literature has tended to observe and model the diffusion process by considering that intra-firm and/or intra-household diffusion (i.e. studies of extent of use by individual actors) is a separate process from inter-firm or inter-household diffusion (i.e. studies of the proportion of the population using the technology at any positive level). We will continue to follow this useful convention. We will also, for reasons of length and practicality limit the work to diffusion within a single economy i.e. we will not discuss the international transfer of technology, although our impression is that the theoretical tools we discuss can just as effectively be applied to that issue.

The structure of the rest of this paper is conditioned by my own views as to what is and what is not important in this area. The first preconception reflected in the structure is that the observed stylized facts, like all such observations in economics cannot be the result of solely demand side phenomena. Thus although the first step (section 2), is to consider demand based models, we complement this by a study of supply and supply-demand interaction (section 3). In section 4 I consider the link between diffusion and R & D. Next, because it is often considered that government could and/or should intervene in the technological diffusion process we consider policy issues (section 5). In section 6 I draw some personal views on the most productive avenues for future research and provide a short conclusion.

2. Demand based models

I often find when discussing technology related issues that a mention of Schumpeter somewhere near the beginning enables one to catch the attention (if not the sympathy) of the audience. It is appropriate therefore that I should want to start with Schumpeter's views on diffusion. In Schumpeter (1934) the diffusion process of major innovations is the driving force behind the trade cycle (the long term Kondratieff cycle), however the forces driving the diffusion process per se are not made particularly explicit. The conception is that an entrepreneur innovates and the attractiveness of attaining a similarly increased profit and the pressures on the costs of old technologies in a new regime encourage others to imitate, this imitation representing a diffusion process.

One could attempt to make the underlying theoretical approach more explicit and rigorous, but I find this is somewhat unnecessary. The reason is that, surprisingly perhaps, I consider that some of the most recent and most explicitly mathematical work on diffusion, is modelling precisely the process that Schumpeter was describing. Athough beginning with this work rather overturns the historical flow of the survey I find there is some advantages in starting here. The view to which I am referring can be called game theoretic or strategic, but I just prefer to associate it with Reinganum (1981(a), 1981(b), 1983).

The assumption is that there is an n firm industry in which all firms are the same and all have perfect information. There is a new cost-reducing, capital embodied process innovation available, the cost of adopting which falls over time (at least until some distant date). It is then shown that under certain conditions the firms in the industry will adopt at different dates and thus a diffusion path may exist. The actual proofs in the papers are not simple and the presentation is very mathematical. I will here, therefore, present a more conceptual version of the argument, hopefully without too much cost to the original.

Let firm i's profits when m other firms are using the new technology be $\pi_1(m,n)$ if it is also a user and $\pi_0(m,n)$ if it is a non user. Both $\pi_1(m,n)$ and $\pi_0(m,n)$ will decline with m (and n), for as use of the technology extends firms will increase their output and prices will fall. Of course $\pi_1(m,n) > \pi_0(m,n)$. Let the costs of adopting the technology in period t be C_t. A firm behaving myopically (on which we say more below) will adopt the new technology[1] in time t if

$$\pi_1(m,n) - \pi_0(m,n) \geq C_t \tag{1}$$

1. The intra-firm diffusion is assumed instantaneous, <u>all</u> production being immediately transferred to the new process.

i.e. if the profit gain from use is greater than the cost of adoption. On the assumption that the profit gain declines with m (*i.e.* that the further is the firm down the adoption queue the lower is its profit gain) and also that when m equals n , the profit gain is less than C_t , then (1) as an equality will yield $m<n$, and diffusion will not be instantaneous. There is of course no way of identifying which of the identical firms is a user and which a non user. To produce a diffusion path, C_t is assumed to fall over time and as it does so, so usage increases. Without being explicit I think it is clear why I should consider this Schumpeterian in conception, although perhaps in the work of Schumpeter C_t would be considered more endogenously determined than we have it here.

Reinganum's model is more complex than this simple conception largely because the myopia assumption is not used, and maximisation over an infinite horizon is considered. However we prefer to deal with such complications in an alternative framework below.

I find the Reinganum model particularly useful as a starting point[1] for (a) it assumes that all firms are the same and have perfect information, which we will see is equivalent to removing the basis for diffusion in a number of the models we discuss below, yet it still produces a time intensive diffusion process and (b) the structure of the model illustrates the basic form of many diffusion models - a decision theoretic modelling of choice behaviour to determine ownership or use at a moment in time allied with some changes in underlying conditions over time that generate changes in ownership over time.

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1. One might immediately observe however that it is probably of little use for analysing consumer good innovations where one expects strategic behaviour among potential buyers to have very little role to play.

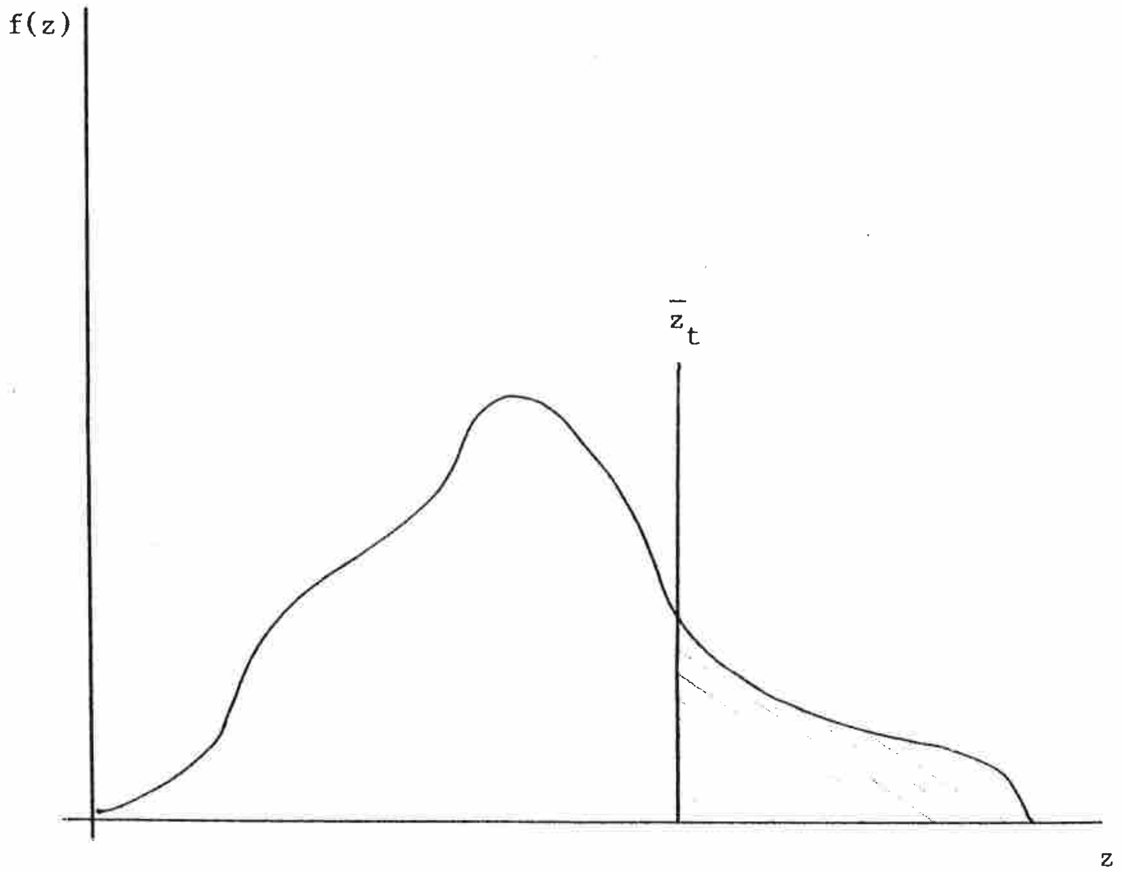
We proceed from here pursuing this structure by next looking at models where potential buyers differ from one another and then turn to the information based approaches.

Probit models

In Reinganum's framework firms were the same, information was perfect but benefits from acquisition declined as usage extended. In the class of models we consider here we maintain the assumption that information is perfect but we assume that acquirers differ from each other. An acquirer's benefits do not decline as usage extends. The diffusion model is then constructed as follows (see David (1969). Let the potential adopters of a technology differ according to some yet to be specified characteristic, z , that is distributed across the population as $f(z)$ with a cumulative distribution $F(z)$, see Figure 1. Allow that in time t , a potential adopter, i , will be a user of the technology if his characteristic level $z_i \geq \bar{z}_t$, some critical level of the characteristic, then the proportion of the population who have adopted by time t is given as $1-F(\bar{z}_t)$. This is shown in Figure 1 as the shaded area. As time proceeds either $f(z)$ is assumed to shift or $\bar{z}_t$ changes (falls) and as such events occur the proportion of users and the number of users changes, thus tracing out the diffusion path.

Obviously this framework needs a great deal of meat adding to it before it is operational. However being very general means that we can use it as a general form for analysing many different approaches to diffusion by specifying the appropriate characteristic. We will be

Figure 1



concentrating below on the use of the model to analyse the diffusion of a process innovation across firms, so we will mention other uses here. We might for example think of a consumer good innovation whereby the relevant characteristic might be socio-economic group or, as used by Bonus (1973) household income. Then ownership extends down the income distribution. We might think of technologies whereby spatial characteristics are important and the distribution reflects this with diffusion following some spatial pattern. Whatever the application the principle is the same.

What is clear though is that we cannot get far until we define the characteristic and the determination of $\bar{z}$. Two of the most successful applications of this approach David (1969), Davies (1979) have considered firms buying process innovations and have isolated firm size as the relevant characteristic, although David (1969) refers to applications considering characteristics such as entrepreneurial attitudes and vintage or age-of-capital effects (vintage models). These applications to process innovations centre upon profit as the criterion for the determination of $\bar{z}$. Thus in David (1969), the technology is assumed to exhibit increasing returns to scale and thus at any time there is a certain size of firm above which it is profitable to adopt, below which it is not. This then defines a critical firm size. Davies' (1979) model although not in the profit maximising mould is very similar.

To illustrate more fully the operation of the model I will not be specific about the characteristics but I will keep the profit motive as central. To proceed we make two further assumptions (i) that when technology is acquired, the firm transfers its whole production to the new process (there is no intra-firm diffusion process) and (ii) the technology can be acquired by purchase of one unit of a new capital good whatever the level of use by the acquirer.[1] Allow that a firm of characteristic level z can by acquisition in time t obtain an increase in his profit flow of $h(z)$ in perpetuity, yielding a present value gain of $h(z)/r$ where r is the discount rate. Also allow that in time t ,

1. By handwaving and say, the treatment of firms as plants the severity of these restrictions can be relaxed.

the cost of acquisition is p_t , with the expected cost of acquisition in the follow period being p^e_{t+1} . A profit maximising firm will acquire in time t if

(a) it is profitable to do so, $h(z)/r \geqslant p_t$ (2)

and (b) it is not profitable to wait until time t+1 i.e.

$$-p^e_{t+1} + (1+r)p_t \leqslant h(z) \qquad (3)$$

One may note that if the buyer is myopic $(p^e_{t+1} = p_t)$, then (3) collapses to (2) and the profitability condition is sufficient to determine use. If buyers have perfect foresight and $p^e_{t+1} = p_{t+1}$ and $p_{t+1} < p_t$, then satisfying (3) satisfies (2) and (3) is going to determine use.

Define z_t as the characteristic level of the marginal adopter in time t , then, under myopia

$$h(z_t) = rp_t . \qquad (4)$$

If the potential population of adopters is of size N , then the number of users in time t , M_t , is

$$M_t = N(1-F(z_t)) \qquad (5)$$

$$\therefore \quad \frac{N-M_t}{N} = F(z_t)$$

$$\therefore \quad z_t = F^{-1}\left(\frac{N-M_t}{N}\right)$$

$$\therefore \quad p_t = \frac{1}{r} h\{F^{-1}(\frac{N-M_t}{N})\} \tag{6}$$

Given that each firm only buys one unit of the new capital good the stock of the capital good acquired by time t , $X_t = M_t$, thus

$$p_t = \frac{1}{r} h \{F^{-1}(\frac{N-X_t}{N})\} \equiv \frac{1}{r} g(X_t) \tag{7}$$

Equation (7) is an inverse stock demand function that relates the stock of the new capital good demanded to the current price of that capital good. If we assume that buyers are not myopic we can define equivalently to (7) the condition (8) as the inverse stock demand function under perfect foresight.

$$\begin{aligned} p_t &= \frac{h}{1+r} \{F^{-1}(\frac{N-X_t}{N})\} + p^e_{t+1} \\ &= \frac{1}{1+r} g(X_t) + \frac{p^e_{t+1}}{1+r} \end{aligned} \tag{8}$$

which may also be written as (9)

$$(p_t - p^e_{t+1}) + rp_t = g(X_t) \tag{9}$$

From (7) it is easy to see how a diffusion path results. Holding r constant, totally differentiating (7), and using the dot convention for a time derivative

$$\dot{p}_t = \frac{1}{r} g_x \dot{X} \tag{10}$$

and $$\ddot{p}_t = \frac{1}{r} (\dot{X} g_{xx} \dot{} + g_x \ddot{X}) \tag{11}$$

From (10) usage extends as price falls, given $g_x < 0$. From (11), $\ddot{X}$, which will tell us whether the diffusion curve is sigmoid depends on $\ddot{p}$, g_x , $\dot{X}$ and g_{xx} . Thus the nature of the diffusion path depends on movement in prices over time and the g(X) function. This in turn will depend upon the h(z) function, i.e. how benefits are related to characteristics and the f(z) function, i.e. how the characteristics and thus the benefits are distributed across the population. As these functions vary so the diffusion path will be changed. By manipulating these distributions, Davies (1979), for example illustrates how the diffusion pattern may be related to the concentration of firm sizes.

A variety of models with demand structures on these lines have been constructed by David and Olsen (1984), Stoneman and Ireland (1983, 1984), Ireland and Stoneman (1985, 1986), Stoneman and David (1986). Two of these papers, David and Olsen (1984), and Ireland and Stoneman (1986) are addressed particularly to an issue raised by Rosenberg (1976), that we can begin to raise in this context. Rosenberg argued that the literature on diffusion took insufficient account of expectations in the diffusion process. He hypothesized that a technology that is expected to improve over time may experience slower diffusion than one that is not. From equation (9), given $g_x < 0$, we can see that for a given p_t , the lower is p^e_{t+1} , the smaller will be X_t , the level of use i.e. firms will prefer to wait before acquisition. It may be profitable to acquire now, but it is more profitable to acquire tomorrow. Rosenberg's hypothesis thus carries some support when expectations on prices are being discussed. Ireland and Stoneman (1986) consider the issue further. Expectations may refer to technological obsolescence, and they show that in certain circumstances, the discount rate r can be interpreted as including an element reflecting the risk of obsolescence, so a heightened expectation of the new technology being supplanted can be modelled by a higher value of r . From (7) or (8) one can see that a higher r would be associated with less use, ceteris parabus. Balcer and Lippman (1984) consider the case of technological expectations more explicitly with similar results.

These probit models suggest therefore that diffusion is the result of movements down some benefit distribution. The speed of diffusion and shape of the diffusion curve depends on the shape of the benefit distribution and the rate at which movement down the distribution occurs. For the moment the rate of movement is being treated as exogenous, we will have occasion below to make it endogenous. The model's predictions as to determinants of the diffusion path for empirical study (of which David (1966), von Tunzleman (1978) and Davies (1979) have done some) does depend on the isolation of the crucial characteristics.

The model we have presented here is free of strategic or information complications so that the basis of the approach could be isolated. It is worth noting however that David and Olsen (1984) do incorporate some strategic elements, and Stoneman and David (1986) grafts information issues on to the basic model. As we shall see however in the next part, information based models often themselves revert to probit type models to generate inter-firm diffusion paths.

Risk, Uncertainty, Information and Learning

Thus far we have ignored one particular characteristic of the diffusion process that should not be ignored and is perhaps of overriding importance. As diffusion concerns something that is new it is probably taking place in an environment where information is imperfect and as a result involves uncertainty and risks.

If the world is one involving uncertainty then the modelling of the decision process must be one that treats decision making under uncertainty. Thus the several approaches we consider in this section have at their core such theories. The diffusion models we cover also all need to ally some learning or information acquisition process with their decision making frameworks. The sources of information can be divided into two classes, external and internal (to the decison making unit), which gives us a possible dichotomy in the classification of diffusion models. A further possible classification in this area is that between inter-firm and intra-firm diffusion models. Some models (inter-firm) consider just whether the potential buyer acquires the new technology or not, others (intra-firm) consider the level of use of the technology by a buyer.

Our starting point is epidemic models. In their simplest inter-firm form it is assumed

(a) that upon learning of the existence of the new technology a potential acquirer will adopt the technology (the decision theoretic framework) and

(b) that information on existence is spread by personal contact, in that whenever a potential acquirer who is a non-user, meets a user, then he obtains knowledge of existence (this information spreading mechanism obviously leads to the label "epidemic").

This very simple combination will generate a time path of diffusion that is logistic, which functional form is often used to approximate the diffusion curve, and the speed of diffusion is related to the frequency of interpersonal contact. The simplicity of the model has led to a number of criticisms (see for example Davies (1979)) on the grounds that the potential adopters are considered homogeneous, no allowance is made for technology improving over time, the information spreading mechanism is too simple and takes no account of other information sources (e.g. advertising) and the decision theoretic framework does not really capture the essence of decision making under uncertainty (to say the least). Even so, the model has a distinguished background in the subject (see for example Griliches (1957) or Pyatt (1963)).

One variation on the basic epidemic model is developed by Lekvall and Wahlbin (1973). They consider that the communication mechanism discussed above (contact with users) should be supplemented with information coming from outside the set of adopters (through for example advertising and other promotional activities). They show that this will produce a diffusion curve that is no longer logistic, the external influences modifying its shape. We might note that both Gould (1970) and Glaister (1974) have looked further at the role of advertising in diffusion models of this kind.

Despite these modifications to the information mechanism, such models as these are particularly weak on the decison-theoretic side. This leads us to what is probably the most widely known and widely used diffusion model. That of Mansfield (1968). This model comes in two forms, the inter-firm and intra-firm models which are largely distinguished by whether the information source is internal or external to the firm. In the inter-firm model, the decision theoretic framework is represented by a reduced form hypothesis. It is argued that at any point in the diffusion process the number of users acquiring the technology at that moment is related to the risk attached to acquisition, the expected profitability of acquisition and the number of potential adopters. The latter two are assumed to be invariant with respect to time, but risk is assumed to reduce as the number of users increases thereby driving the diffusion process. The reductions in risk are assumed to come about because increased ownership or use increases knowledge and this reduces uncertainty. By the choice of appropriate functional forms the model generates a logistic diffusion curve with the speed of diffusion linearly related to, inter alia, profitability.

The intra-firm variant is very similar. The reduced form decision rule relates the firm's extension of use in a period to risk, expected profit and its final level of use. The latter are assumed invariant to time but risk is reduced over time as the firm learns from its own use. Again, by appropriate choice of functional forms, a logistic diffusion curve with diffusion speed linearly related to, for example, profitability is generated.

Despite the undoubted empirical success of the generated estimating equation from these models, the framework has been subject to various criticisms.

(i) The information sources are all internal in the sense used by Wahlbin - risk is only reduced as the numbers of users extends in the inter-firm model or as the firm's usage extends in the intra-firm model, for example, advertising has no role to play.

(ii) It is difficult to see exactly from what decision theoretic framework the reduced form adoption rule is derived.

(iii) Technology is assumed to not change over time (see Gold (1981) , who describes the model as like filling a bottle).

(iv) The treatment of risk, uncertainty and information acquisition has been considered very inadequate see, for example, Stoneman (1981).

To some extent such criticisms as these have been overcome by recent work that more explicitly details the process of decision making under uncertainty. These approaches have been applied extensively in the analysis of the adoption of agricultural innovations in Developing Countries. A recent survey by Feder, Just and Zilberman (1985) summarises much of the theoretical and empirical literature in this area, a fair amount of which can be attributed to Feder (1980, 1982), or Feder and O'Mara (1981, 1982) or Feder and Slade (1984). It appears that, simultaneously, this group, Jensen (1982, 1983, 1984(a), (b), (c)), Stoneman (1980, 1981, 1983), and Lindner, Fisher and Pardey (1979), were all working in slightly different ways towards the same objective - modelling diffusion under uncertainty.

The work of Stoneman and Lindner et al is very similar. A firm is considered that has a choice of using new or old technology. Each technology has associated with it a mean and variance of returns, which are known for the old technology but not for the new. The firm makes decisions on the basis of maximising a utility function defined on the overall mean (profitability) and variance (risk) of it's production mix, by the appropriate choice of the proportions in which the two technologies are being used. In the initial period the firm forms a prior estimate of the distribution of returns to the new technology. As time goes on this prior is updated as new information is gathered. The updating is modelled as a Bayesian process. The updated estimates lead to changes in the desired level of use, thus tracing out the diffusion process.

Lindner et al consider the problem of first use of a new technology and allow that the information sources are external to the firm. Adoption (in terms of first use) will occur when the estimate of the mean return to the new technology is high enough to overcome the risk (variance) attached to it.

The Stoneman version is more concerned with the proportion of the firm's output produced on the new technology once initial adoption has occurred. In this model all information is derived from internal sources. It is thus basically a model of intra-firm diffusion. It is shown that at a moment in time the level of use will depend on

(a) the true mean and variance of returns to the new technology

(b) the mean and variance of returns to the old technology

(c) the initial estimates of the mean and variance of returns to the new technology

(d) the firm's attitude to risk and

(e) the correlation of the returns to the new and old technology.

These models are simply converted to inter-firm diffusion models. Define α_{it} as the proportion of ith firm's output produced on the new technology in time t, and define $\hat{\alpha} \geq 0$ as the level of α above which the firm is defined as a user below which it is defined as a non user. We may then proceed in the manner of probit models. Given the distribution across all firms of α_{it} at a moment in time we can define the proportion of firms for whom $\alpha_{it} > \hat{\alpha}$, and thus generate the extent of diffusion. As α_{it} changes over time so will the extent of diffusion. We are given the determinants of α_{it} above ((a) - (e)) and thus we have predictions as to which characteristics are associated with early users which will late users and what will determine the speed of movement along the diffusion path.

Tonks (1983, 1985) has critisized the work of Stoneman (1981) on the grounds that the model does not allow the firm to buy technology in order to acquire information, the information is being treated as a non-valued by-product of use. The Tonks model thus tries to correct this. It is also unique in this area in concentrating on consumer good innovations rather than producer good innovations. However, the important basic principle of the model is that economic agents will, given that information is valuable, actually undertake search rather than wait for information to arrive.

Jensen has considered this possibility and is one of the few authors to do so. In his early papers, he does not however. In Jensen (1982), he considers a firm that receives external information about a potential innovation. It does not know whether the innovation will be profitable or not, but the information allows it to learn. Adoption is an all or nothing decision. The firm is assumed to use Bayesian updating rules and at each moment in time can make one of three decisions (i) acquire (ii) not acquire (iii) await further information before making a decision. The decision to adopt is considered irreversible and decision makers are risk neutral, acting to maximise expected returns. The decision problem is shown to be an optimal stopping problem, and the optimal behaviour of the firm is shown to be to adopt when its current belief that the innovation is good is above a minimum reservation level, which in turn is dependent on the cost of adoption, the return to the technology and the discount rate. Setting the decision up in this way leads obviously to an inter-firm diffusion model using probit methods. In Jensen (1983), the model is extended to choice between competing innovations. In both cases it is shown that S shaped diffusion curves can be predicted. Reinganum (1983), explores a very similar model.

In Jensen (1984)), the model is extended to allow more than one information message per period, but most interesting are Jensen (1984(a) and 1984(b)) where the information is treated as costly to the firm i.e. the firm has to pay for information. Jensen argues that if learning is costly then immediate adoption becomes more likely and delayed adoption becomes less likely, and eventual adoption of a profitable innovation is not certain. This is as one would expect, costly information will only be acquired if the expected gain from having that information is greater than its cost. Some firms may thus never learn about an innovation that is profitable to them for they are unwilling to pay for the information.

This growing literature has a number of useful results. It emphasises attitudes to risks, priors and updated estimates of risks and returns etc. as important in the diffusion process. It also allows firms to make mistakes so unprofitable innovations may be adopted leading to a possible eventual reversal of the diffusion process. Even so, there are problems, in particular as far as I know, this literature ignores the possibility that technology may improve or become cheaper over time and it still tends to treat diffusion as "filling a bottle".

Behavioural and Evolutionary Models

Each of the frameworks we have described above although they might include imperfect information and uncertainty maintain the long neo-classical economic tradition that economic actors are maximisers. An alternative line may be that firms satisfice or use rules-of-thumb decision making processes. Perhaps the main proponents of this view today in the technological change literature are Nelson and Winter (1982) with their evolutionary models. I have also published some work on this line myself, Stoneman (1976). The work however is not easy to summarise briefly. The main characteristics of the approach are those that will be familiar to students of behavioural theory *i.e.* satisficing, local search, problem orientated decision making etc. Nelson and Winter, pp 262-267, discuss diffusion in a framework very similar to the framework used here *i.e.* decision processes, information spreading processes, risk and search etc. One of their main contributions, although not completely absent from the discussions above, is their emphasis on variety. Different innovations in different industries will have different diffusion patterns (agriculture is not like aircraft); public corporations may behave differently from private firm; and the regulatory environment may also affect the diffusion path. We are warned therefore to be wary of over-generalisation.

3. Supply and Demand

The modelling frameworks we have been discussing have considered the demand side in the diffusion process. However, although such demand models have in some cases been used alone to explain observed diffusion phenomena, in general, any realised diffusion pattern must be the result of not just a demand pattern but of a supply/demand interaction. This requires, if we are to fully understand the diffusion process, that we have some insight into the supply side as well as the demand side, and some knowledge of the interaction between supply and demand. I am going to assume that the typical innovation is produced in one industry and then sold to another industry or to the consumer. It may be the case that for some innovations that the buyer and seller are in the same industry, but I do not discuss that case. I will also assume that the supply industry is a domestic industry. Some technologies may be bought from overseas but I do not consider that case. We may note that for the supplying industry the new technology will be a product innovation, for a buying industry it will be a process innovation.

The modelling of the supply side is designed to generate (a) a supply curve relating for each time period the quantity at each price the industry is willing to supply (b) a time path for technological improvements and (c) a resolution of any conflict between quantities supplied and demanded. To investigate such issues it is clear that one must model (a) the time structure of the supply industry's costs (b) the capacity of firms in the supplying industry (c) the number of suppliers (d) the price and quantity setting behaviour of firms and (e) the nature of market interactions, stated in this way it soon becomes obvious that such issues represent a major research area that is not only of interest in the study of diffusion. However, having said this, our knowledge of supply industry behaviour especially in the context of diffusion is very limited. To illustrate this point, I have argued that for the supply industry, new technology will represent a product innovation. Competition between firms may thus come down to product innovation competition, and thus the appropriate way to model such a market is a method involving product differentiation. As economists we are limited in our ability to do this at the present time. One possible approach is illustrated in the work of Shaked and Sutton (1982, 1983) but as far as I know this has not been applied to the diffusion problem as yet. A major research opportunity exists here.

To illustrate the work that has been carried out we start by considering Ireland and Stoneman (1986). In this paper the supply industry is assumed to be a n firm symmetric oligopoly (of which $n=1$, monopoly and $n \to \infty$, perfect competition, are the special cases). Firms are assumed to be quantity setters with Cournot conjectures. Firms are assumed to know the demand regime (which is of the probit type as represented in eqs (7) or (9) above), and maximise their present values. The costs of production are assumed to fall exogenously over time. Diffusion proceeds by firms reducing prices over time which increases use by movements down the reservation price distribution over potential users. In this particular paper the main question approached is how the buyer's expectation regime will affect the diffusion path. The results indicate that

(a) for a given number of suppliers diffusion will be faster if buyers have perfect foresight on prices rather than hold myopic expectations

(b) that, given the expectations regime, the greater the number of suppliers the faster is diffusion, but

(c) perfect competition in supply with buyers having perfect foresight yields the same diffusion curve as a monopolist supplier combined with buyers who are myopic.

There are now a number of variants on this model. One variant is to consider that suppliers costs do not fall exogenously but reduce with accumulated output (learning by doing). An important issue here is whether the learning by doing is firm specific or industry wide. The learning by doing variant is explored by David and Olsen (1984), and Stoneman and Ireland (1983). David and Olsen also incorporate a slightly different demand structure in their model, with some strategic elements in it. Another probit variant with early mover advantages on the demand side is explored by Stoneman and Ireland (1985). I know of work proceeding with a demand side modelled on Reinganum lines, but I do not know of any work adding a supply side to a demand side framework in which decision making under uncertainty is modelled formally. There is an early paper by Glaister (1974), that treats demand as epidemic model based, and Stoneman and David (1986) combine a supply side with a mixed epidemic/probit model.

Although this does not represent an exhaustive list of work proceeding on these lines, it suggests that the area is very active. However, there are problems with this work. Not the least of these is that as constructed these models assume that over the diffusion period the number of suppliers is constant. The empirical work of Gort and Klepper (1982) shows that this is not a reflection of reality. Some modelling attempts have been made e.g. Stoneman and Ireland (1984) to make the number of suppliers endogenous, but they have not really come to grips with the question, what determines the number of producers of a new product? I do not really think that economics has a complete answer to this. Spence (1979, 1981) has made some advances in this area, and in my book Stoneman (1983) I make an attempt to survey the relevant literature. It seems to me however that there is still much to do here. I do in fact return to this issue below.

The work already referred to has other limitations. First it assumes that markets always clear. There is some evidence (see e.g. Stoneman (1976)) that firms' prices will not always clear the market and orders or inventories may build up. As far as I know such non-price adjustment mechanisms have not been formally modelled. Secondly, except in the case of Glaister (1974), the possible use by the suppliers of advertising or other forms of non-price competition, tends to be ignored. Finally, the models so far discussed tend to abstract from the problems of capacity. A firm selling a new product for which demand is likely to grow and then fall faces a number of problems (a) should it install capacity to meet peak demand or try to smooth demand and hold reduced capacity? (b) can it raise sufficient funds to provide the capacity required? (c) how should it fund its capacity creation? Metcalfe (1981, 1983), has been a major contributor to work on diffusion that stresses this capacity problem on the supply side.

I consider the addition of the supply side to be the most important advance in the economics of diffusion of the last ten years. This is not only because it throws new light on the determinants of the diffusion process (supply industry structure, costs, behaviour etc) but because it allows us to make two further advances, the first in linking diffusion to R & D, the second in the policy area.

4. Diffusion and R & D : The Interaction

There has been some limited debate in the literature on the impact that R & D by a potential user can have on the diffusion process (see e.g. Mowery (1983)). The R & D so discussed can be expenditures on adapting technology to a firm's particular circumstances or R & D as search expenditures. In terms of formal modelling this is largely the same as considering search to be costly and we considered it above by reference to the work of Jensen (1984(a)). Here I am after a different link.

When we add a supply side to the diffusion process, we know that the number of suppliers and their costs and the improvements in technology that they generate are important influences on the diffusion path.

However, production costs, improvements in technology, and entry to an industry are largely the result of R & D spending. The incentive to do R & D is expected profitability. This profitability is derived by the suppliers from sales during the diffusion process. Thus the diffusion process generates the incentives to R & D and R & D brings forth the lower costs, improved technology etc that drive the diffusion. At the risk of overemphasis, the point being made is that R & D (or invention and innovation) and diffusion are not separate processes. They are in fact an integrated process. The integrated nature of this process has not been fully realised in the literature. There is some formal modelling in Stoneman and Ireland (1984) and also Metcalfe (1985) has been approaching issues on a similar line of enquiry. Perhaps of more importance however is that it brings into diffusion analysis the huge body of work on R & D, although I have no intention of summarizing it here. That R & D literature is concerned with the generation of new products or product improvements, with new processes or process improvements, with technological competition between firms etc, all of which are factors that underlie the supply side, the role of which in the diffusion process we have already emphasised. My message is that it may be time to think of re-integrating the Schumpeter trilogy.

5. Public Policy

Policies on diffusion have in most economies been the poor relation to R & D policies in overall technology policy strategies. Despite the fact that the impacts of new technology only arise as new technology is diffused and inventions and innovations that are not diffused have no impact on the economy, it is the support of invention and innovation that has taken the lion's share of most technology support programmes. Diffusion policies, where they have been put into effect, tend to be small and generally of two types - information based policies e.g. the U.S. Agricultural Extension Scheme or subsidy policies e.g. the U.K. government in the late 1960's subsidised the purchase of digital computers.

As our conception of the diffusion process has broadened to encompass the supply side and the links with R & D the view that we take of policy initiatives has changed. These changes are best treated by recourse to a list.

1/ I do not think it a misconception of much of the early writing in this area to say that the view commonly held was that "technological change is good and faster technological change is better" and thus faster diffusion should always be encouraged. There are some hints of dissension from this view e.g. Tisdell (1981), Nelson Peck and Kalachek (1967). Recent advances however have allowed us to be more explicit. The supply/demand models of diffusion allow one to characterise welfare optimal diffusion paths. Welfare optimality does not always imply the fastest possible take up of technology and thus the maxim that faster is better does not always hold. Obviously, deciding on optimality requires statement of the welfare objective function. In the various papers by Stoneman and Ireland discussed above, welfare is defined as the sum of suppliers' profits and users' profit or utility gain. This could be extended in the case of process innovations to include additions to buyers' consumer surplus.[1] In Stoneman and Ireland (1986), the welfare

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1. These definitions are appropriate in a world in which markets clear. When markets do not always clear one might, for example, use employment as a welfare indicator.

optimal path is shown to be generated by either a competitive supplying industry with buyers with perfect foresight or by a monopoly supplying industry with buyers who are myopic. Myopia with a competitive supply industry yields diffusion that is too fast, perfect foresight with monopoly supply yields diffusion that is too slow. To illustrate that the nature of the optimal path is rather model specific we might note that David and Olsen (1984) have a different welfare optimal path because the costs of producing the new technology fall by learning by doing whereas in Stoneman and Ireland they fall exogenously. To further illustrate the fragility of the result, the Stoneman and Ireland (1986) result is dependent on the returns to the new technology being unaffected by the diffusion path. However under perfect competition suppliers get no profit, under monopoly suppliers get maximal profits. Thus although we can generate the same, optimal, diffusion path of a technology under different supply regimes if expectations of buyers differ, the incentives to do R& D are very different under the two regimes and thus a welfare definition that also considered the generation of technology would not judge the two paths as equally desirable. The implications of this are explored in Ireland and Stoneman (1984). One might further note that the assumption that the new technology is domestically produced is crucial to the results.

2/ The linking of diffusion to R & D means that technology policies aimed at diffusion will affect R & D and policies aimed at R & D will affect diffusion e.g. stimulation of a new industry through R & D support may make available cheaper or better products that stimulate faster diffusion. Similarly, stimulating use may improve incentives to R & D in the supply industry.

3/ The consideration that supply is also important leads one to argue that supply side reaction to demand orientated policies is an important factor to consider in evaluating the potential effect of policies e.g. if supply capacity is limited, stimulating demand may only lead to higher prices and not greater diffusion. In Stoneman and David (1986), the reaction of a monopoly supply industry is compared to the reaction of a perfectly competitive supply industry, when information and subsidy policies are used to speed diffusion. It is argued that the monopolist may react to negate the intention of information policies and the policies may not work. A competitive supply industry will not so react and information policies will speed diffusion, but subsidy policies under competition may lead to use of a new technology by firms for whom it is not profitable and this may reduce welfare.

4/ Finally, recent advances incorporating expectations into the diffusion process have shed new light on policy analysis. In particular if subsidies are expected and if stimulation of technological improvement or extensions of use are expected , then these expectations may lower current adoption rates.

Analysis that incorporates these sorts of considerations is limited. In a couple of papers however, David and Stoneman (1984) and David (1985) a variety of these issues are discussed.

Conclusions

In this survey I have attempted to move away from treating the problem of diffusion as an exercising in finding the right S shaped curve to fit the data and I instead look at the underlying theoretical bases being discussed as foundations on which to approach the analysis, understanding and policy implications of diffusion processes. The literature I have surveyed now often tends to be of a high degree of mathematical complexity but I have tried to minimise this in the survey. Moreover most of the literature I have surveyed tends to be rather neo-classical in sentiment. I do wonder if I have really done justice to the "political-economy" literature. Having said this however it is clear that recently, numerous advances in the theory of diffusion have been made, these suggesting that the phenomenon needs much more sophisticated treatment than has been common in the past.

It is appropriate that I finish this survey with my own views as to where research ought to go from here. I suggest basically four potentially fruitful lines.

(i) There is an obvious need for empirical (econometric) work looking at the new factors recently introduced into diffusion analysis *i.e.* expectations, supply sides, Bayesian learning etc.

(ii) We need to have much greater understanding of the growth of capacity, number of suppliers and market structure development of industries producing new products. This will obviously interact with the R & D literature.

(iii) We need further work on the explicit modelling of *product* innovation and associated with that, work on advertising and marketing. These latter issues have probably been treated more extensively by management scientists than economists.

(iv) Finally, there is an obvious need for much more work on the policy implications of the theory of diffusion. It is no longer just a matter of discussing instruments, our recent advances enable us to discuss optimality, divergence from optimality and policies to correct this. The fact that this makes policy analysis more complex is the cost, but it also makes it much more interesting.

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