Ed Mansfield and the Diffusion of Innovation: An Evolutionary Connection

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ABSTRACT. The analysis of the diffusion of innovation was a central theme in Ed Mansfield's work over many years. In this essay I summarise his analysis of logistic diffusion processes and relate his work to earlier studies of industrial retardation and subsequent work on evolutionary economic processes. A distinction has to be drawn between the logistic law and the logistic curve, the latter being only one instantiation of the more general law which is itself a signature of evolutionary selection processes within a population of rival innovations.

Key words: innovation diffusion, logistic law, evolutionary process

JEL Classification: D23, O31, O32, O33

1. Introduction

Ed Mansfield was an acknowledged pioneer in the study of technological change and its wider economic consequences. Along with Zvi Griliches, Dick Nelson and Chris Freeman he was a premier source of inspiration to the generation of scholars who began to study technical change in the 1960s. In terms of the range of his interests, the sharpness of the questions he posed and his willingness to gather the detailed micro data that is needed to make sense of technological change, he had few peers in his generation. Others have written extensively about his work (Diamond, 2003; Scherer, 2005); in this short essay I want to relate his contribution to the wider framework of evolutionary economic analysis for, unwittingly or not, it is to this field that Mansfield made a major contribution particularly though his work on the spread of new technology. The connection to evolutionary ideas is through Mansfield's use of the logistic curve, one of a ubiquitous family of "S" curves to which scholars have turned to summarize the evolutionary dynamics of the spread of innovations. Less well known is the fact that behind the logistic curve lies a more general logistic law describing the relative diffusion of competing innovations in a population of technologies that serve some common economic purpose. It is the logistic law that predisposes population dynamics to generate logistic curves when the diffusion data are plotted over time. The logistic has for many years been a standard tool of analysis in evolutionary ecology (Kingsland, 1985) and in evolutionary economics it is a way of capturing the dynamic response of a market system to the opportunities opened up by economic variation in the form of sequences of innovations. In this brief essay, I shall explore two particular aspects of Mansfield's work on diffusion, in relation to the further developments in diffusion theory that it stimulated, and in terms of the longer sequences of evolutionary economics that pre-date and post-date Mansfield's work. It turns out that Mansfield's work is closely connected to wider questions subsequently studied by evolutionary economists, indeed that the logistic law, the logistic process and the logistic curve are characteristic signatures of competitive selection processes in the presence of economic variation. In short, I shall argue that logistic phenomena are deeply embedded in competitive evolutionary processes but that these processes do not generate in general a logistic curve when the diffusion data is plotted over time. The logistic law and the logistic curve must be separated conceptually, and only in special cases will the later follow

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from the former. Indeed the logistic curve is a very special case of the more general logistic law, which is perhaps why there exists a whole family of "S" curves, Gompertz, log-logistic, log normal etc., that can provide good competing, empirical summaries of the diffusion process. The deeper content of the logistic process it turns out is that it is a natural consequence of a population approach to evolutionary dynamics.

The modern literature on innovation diffusion is immense not only in economics but in marketing management and in technological forecasting and I don't propose to review it at all.[1] However, some brief assessment of the Mansfield approach will help the subsequent discussion.

2. Mansfield on innovation diffusion

Amongst the most influential of his papers are the studies of the spread of new technology, for as he put it "Once an invention is introduced for the first time, the battle is only partly won, since it must still gain widespread acceptance and use. The rate of diffusion is of great importance. The full social benefits of an innovation will not be realised if its use spreads too slowly" (1971, p. 133). Here Mansfield identifies themes of great importance in his future work; that the economic and social payoffs from innovations depend on the diffusion of those innovations, a problem in economic dynamics, that there might be an optimal rate of diffusion which ultimately would determine the private and social returns from investments in practical knowledge and in its more abstract underpinnings in science and basic engineering.

Here I propose to focus on the 1961 paper on the diffusion of innovation since most of his subsequent ideas and studies on innovation diffusion remain framed by this seminal paper. Mansfield begins with a question "Once a new technique is introduced into an industry by a firm how quickly will others make use it?" His answer is grounded in Schumpeter's distinction between the initial innovator and the subsequent swarm of imitators who carry the innovation to its full economic significance. By taking 12 innovations in 4 industries and using data gathered from major firms he observes that the rate of adoption is generally slow with wide variations across the innovations. Clearly this is a problem in dynamic adjustment, and Mansfield's general approach to the problem is that the spread of new technology is part of a market process which sets the dynamic context in which producers and users respond to new technological opportunities. He suggests it is a process of learning, and thus of the growth of knowledge in the market context, in which producers and users improve the innovations in focus and, when they are stabilised, then shift their attention to improving the associated process technology. This is a theme that has been explored in depth in the subsequent product and technology life cycle literature (Utterback, 1994) but it is clearly contained in Mansfield's general approach, albeit in a form subdued relative to the questions to which he devoted most attention. Among these questions the three most important are "What factors explain the different rates at which innovations spread?" "What factors explain the rates at which different firms adopt innovations at different times?" and "What factors determine the speed with which a given firm substitutes new methods for old in its operations?" The answer to the first question is of course a logical extension of the second and third although the three are often treated separately. In the 1961 paper, for example, the focus is on the first question and we find that it takes 5–10 years on average before half the firms in an industry begin using an important innovation and in many cases longer, although there are wide variations around the average. On the basis of this framework one is led to a number of important distinctions. The diffusion of innovation should be distinguished from the adoption of innovation, the latter relating to the decisions by firms to incorporate an innovation in their activities, the former to the economic importance of an innovation as measured by, for example, the proportion of the output of an industry that is produced with a given innovation. Adoption obviously influences diffusion but it is the latter that embodies the economic impacts of an innovation on employment, rates of return and the competitive process. Indeed, the wider significance of these phenomena is that they provide the link between innovation and productivity growth in particular and economic growth in general. Adoption between firms is distinguished from adoption within firms since it may take many years for a firm to completely adjust its methods of production to a new innovation and, of course, the overall rate of diffusion will depend on the product of the inter-firm and intra-firm adoption rates. In a subsequent study of railroad dieselization, for example, Mansfield reports that of 30 randomly chosen railroads over 70% took more than eight years to fully adopt the innovation while 10% took more than 14 years.[2]

The characteristic feature of Mansfield's explanation of these findings is that they relate to decisions to invest by the respective firms. His innovations are typically capital goods innovations, new plant or equipment, and so the variables used to explain adoption behaviour are profitability and capital cost in some form together with a range of ancillary variables, (durability of the capital equipment is one such) that rarely find statistical significance. Thus Mansfield's principal, deterministic model twins together the theory of adoption and a theory of investment.[3] How does it work?

The explanation is built around a two stage procedure. In the first stage, he begins by defining a measure of the change in the number of adopting firms in some time interval, expressed as a proportion of the firms that had yet to adopt at the beginning of the interval. This measure of the change in "holdouts" is made to depend functionally on the proportion of firms that have adopted by the beginning of the interval (the current adoption rate), and the investment and other variables noted above. This functional dependence is approximated by a Taylor expansion in which terms of third and higher order are dropped and an initial condition is set.[4] The combination of these assumptions leads to the conclusion that the change in the number of adopting firms is defined by a logistic process with constant parameters relating to the maximum number of potential adoptors of the innovation, the intrinsic rate at which adoption increases and the initial condition. The outcome is a predicted logistic curve for the diffusion process which is then fitted successfully to the data for the various innovations to obtain in particular an estimate of the intrinsic adoption rate. Having established a logistic curve as the characteristic signature of the adoption process, Mansfield moves to the second stage to explain the differences in the intrinsic rates of adoption by reference to the investment variables and finds that profitability and capital cost typically account for nine tenths of the statistical variation in the intrinsic adoption rates. In further elaborations, the durability of equipment, the rate of expansion of the adopting firm, and the phase of the business cycle are not found to provide any improvement in the statistical explanation of the cross innovation rates of adoption. This is Mansfield's general approach which he used in numerous other studies including ones where it is the diffusion rate rather than the adoption rate that is investigated.[5] In these other studies the theory of investment is embellished to consider the effects of market structure, firm and industry characteristics such as R&D expenditure, liquidity, and the dispersion of the profitability of adoption but always within the same broad framework.

The methods may look crude by today's standards but in the 1960s they were truly path breaking even acknowledging the caveats that Mansfield always applied to the quality of his data. Anyone interested in the penumbra of topics related to the spread of new technology could not but be influenced by Mansfield's work. His influence on the study of technical change was profound.[6] Almost half a century on, "What are we to make of this as a framework for explaining adoption and diffusion?" Clearly a great deal. Mansfield's insights on the link between investment and adoption have been modified by others but the broad approach remains intact. This is not to say that it cannot be improved upon as a consideration of the following issues shows.

The first general problem is that, *pace* Mansfield, there is no particular reason to expect that the parameters of the logistic process should remain constant over the adoption or diffusion process. Although the underlying process is logistic for given parameters there would be a branch of a different logistic curve for each set of those parameters and so the overall envelope of these branches need not be logistic. As Geroski (2000) points out, many empirical diffusion curves are positively skewed with an inflection point at less than half the saturation level of diffusion as, for example, with a Gompertz curve, and this degree of skewness may simply reflect the rate of time variation of the key parameters. The lesson here is simple but important; even if the underlying dynamic process is a logistic process its realization over time may not trace an exact or ''naïve'' logistic curve. For example, if the saturation level is growing exponentially then ultimately the intrinsic rate of diffusion rate must converge to that same exponential rate. Similarly, if the saturation level is increasing also as a logistic curve then the compound diffusion curve may appear as a logistic built on a logistic, not as a simple logistic curve.[7] Consequently, we cannot deduce the nature of the underlying dynamics simply from an observation of the shape of the diffusion curve.

This is one matter when the supposed changes in parameters are exogenous but quite another when they are varying endogenously because of the diffusion process itself. Then the ensuing diffusion envelope and the variables explaining diffusion rates are generated simultaneously by the diffusion process and again it may or may not be realized in a logistic curve even when the underlying dynamics are logistic.[8] Two broad kinds of factors may produce this result. The first recognizes that diffusion and adoption are not exclusively demand side phenomena, the capacity to supply the innovation is a coequal factor in determining the rates of adoption and diffusion. The rate of diffusion must, in general, depend on the supply capacity of the industry making the innovation and, unless this is perfectly elastic, the parameters of the diffusion process will reflect a mix of demand and supply side forces.[9] As a consequence, the economic characteristics of different innovations may be expected to vary over the diffusion process as capacity to supply is kept in balance with the growth of demand. In Mansfield's terms, both the capital cost of the innovation and the profitability of adopting the innovation will vary endogenously during the diffusion process and indeed are explained by that diffusion process in such a manner that the rates of diffusion and the values of the investment variables co-evolve. The parameters of the resulting diffusion curve have to be interpreted in terms of some amalgam of supply and demand influences, which is entirely consistent with Mansfield's general point about diffusion being embedded in market processes.[10]

The second broad set of factors that extend Mansfield's approach reflect post-innovation improvements in a technology. Any innovation is usually the prelude to a sequence of improvements, major or minor, many of which follow through learning effects by suppliers and users.[11] What is being diffused is not usually a single innovation but rather a design opportunity in which the evolution of design is not invariant to the process of diffusion but reflects diffusion induced learning. Moreover, it is misleading to focus solely on the innovation that is being diffused and thereby lose sight of any improvements that may follow from the rival technologies that it seeks to displace. The sailing ship effect has long been recognised by scholars of technical change but it should really be part of every study of innovation diffusion. Diffusion curves then reflect endogenous rates of improvement across the population of competing innovations not only improvements in the innovation that is the focus of attention. The obvious conclusion is that market and technology co-evolve and that innovation induced diffusion induces innovation.[12]

The above is only a small selection of the theoretical and empirical issues stimulated by Mansfield's pioneering work but they are sufficient to underpin the point that a logistic process and a logistic curve are quite different notions and we should be careful not to assume that one always implies the other. Moreover, what matters is the underlying dynamic process not the particular shape of the diffusion curve, and to deduce the former from the latter is not necessarily an easy task. Then we have the basis for a far richer analysis of diffusion and adoption phenomena. Rather than explore this point further in terms of work post Mansfield it will first be more instructive to go backwards in time to make the point that Mansfield's work on diffusion was part of a broader tradition in which the ubiquitous ''S'' curve played a central role.[13]

3. Retardation theory and the diffusion of innovation

The theme explored here is that Mansfield's diffusion work is part of a far broader tradition of work on the economic dynamics of technical change in which innovations and the response to them are emergent consequences of market processes. The link between all of these literatures is the ubiquitous "S" curve of which the logistic is one of the more easily handled examples. The origins of the logistic curve are normally associated with the biologists Pearl and Reed who were concerned to uncover laws of biological population growth at the turn of the 19th century, and whose work led to the development of a mathematical ecology in which growth curves such as the logistic played a key role. Lotka's (1924) treatise, *Elements of Physical Biology*, provided the definitive statement of this literature. It was obvious to many, including Lotka, that this analysis had strong implications for the laws of growth of an economy in which the structure is continually changing in response to innovation and the rise of new industries and firms. Numerous isolated studies of industrial growth using "S" curves followed (Prescott, 1922; Windsor, 1932; Bratt, 1936; Vianelli, 1936)[14] but it was left to the leading American interwar economists Simon Kuznets and Arthur Burns to develop a more sophisticated and general growth curve analysis applied to the output of specific industries. Kuznets and Burns each built their work around a particular property of "S" curves, including the logistic, namely the phenomena of growth rate retardation. Retardation refers to the fact that the rate of growth of the variable in question, say output, declines continually with time and with the increasing scale of output.[15] This is the phenomena that Abramovitz (1989) identified as one among eight salient empirical generalisations about the process of economic growth.

Both Burns and Kuznets were concerned with the measurement and explanation of secular or long time movements in the volume of economic activity. Both emphasised that the introduction of new activities and the disappearance of old activities are an intrinsic part of the development of capitalism. Both understood that the evidence for retardation would depend on the level of statistical definition of an industry or sector, and that the broader the aggregate the more the evidence in favour of economic evolution and their underlying causal processes will be suppressed. Accepting that the modern economic system is "characterized by ceaseless change", neither could proceed with an aggregate analysis of growth nor accept the idea of uniform progress in all branches of economic activity.

Like other empirically minded scholars, Burns gathered a great deal of evidence to establish that a central feature of modern economic development is the diversity of growth rates of output across different sub-sectors and commodities in the economy. His list of the innovations that underpin the diversity of industry growth rates has a thoroughly modern ring to it. It includes new commodities; new raw materials; changes in methods of production; new methods for the recovery of waste products; changes in forms of industrial organisation; increases in the number of uses of given materials and in the number of materials put to a given use; and, finally, the emergence of what he calls learning products and style goods. In sum, Burns claimed that "These changes have resulted in an increasing divergence of production trends for they have served to stimulate or depress but to an unequal extent, the development of various industries" (p. 63).[16]

Kuznets (1929, 1954) had independently explored the same themes and from a broadly similar perspective. He stated the problem clearly as follows:

> "As we observe various industries within a given national economy, we see that the lead in development shifts from one branch to another. A rapidly developing industry does not retain its vigorous growth forever but slackens and is overtaken by others whose period of rapid development is beginning. Within one country we can observe a succession of different branches of activity in the vanguard of the country's economic development, and within each industry we can notice a conspicuous slackening in the rate of increase" (Kuznets, 1929, 1954, p. 254).

However, this recorded unevenness of growth experience is only part of the picture. For both Burns and Kuznets focused upon a consistent empirical regularity in the process of growth, namely retardation. Their explanations of retardation are remarkably similar and they include population growth (a minor element), foreign competition, inter-industry relations of competition and complementarity and, of vital importance, technical progress. Indeed, for both

Kuznets and Burns, it is retardation in the within industry rates of technical progress, which is the chief explanation of retardation in rates of output growth. Moreover, their theories of technical progress are essentially the same, namely that any industry is created by a particular broad invention, or complex of innovations that offers scope for a myriad of improvements of ever decreasing importance. Progress inevitably slackens, and unless there is some radical breakthrough in the foundations of an industry's methods it becomes increasingly difficult to extract further improvements in performance. This is a view beautifully and subsequently expressed by Hicks (1977) who wrote in terms of the "economic children" that follow the original invention. A sequence of initial inventions creates new activities and a potential design space to explore the possibilities latent in the new concepts and so provides the stimuli to maintain a trajectory of technical innovation over time within the limits resident in these new concepts. This is a theme familiar to all modern evolutionary minded scholars and students of innovation (Dosi, 1982; Georghiou *et al.*, 1984).

Kuznets and Burns were not the only scholars to explore these themes. Fabricant (1942) too found compelling evidence for the retardation of growth in American manufacturing output and employment over the period 1899–1939, although he worked in terms of broader commodity groups rather than the individual commodities that were the focus of the Kuznet's and Burn's studies. While Fabricant does not develop the logic of the retardation thesis, being content to echo the Kuznets/Burns line on technical progress, his study is valuable for its emphasis on structural change and the shifting balance of employment within the overall growth of the economy. Subsequent studies by Hoffman (1949), Stigler (1947) and Gaston (1961) further explored the empirical basis of the retardation theme in different bodies of industrial data but without any further development of the underlying theory. Unfortunately for the study of economic change, growth theory had taken by then its macro economic turn as the consequences of the Keynesian revolution percolated through to the study of long period problems. In all its essentials, the picture of economic growth as the evolving self-transformation of an economy was lost in its entirety.[17]

What brought the logistic and retardation back into modern focus was precisely the literature on the diffusion of innovation and subsequently on industrial and technological life cycles towards which Mansfield made such an important contribution. Any analysis of the logistic curve contains within it an implicit analysis of retardation. Where Kuznets, Burns and others found this at the level of industry and sector aggregates, Mansfield discovered it at the level of individual innovations and thus brought back onto the research agenda a central characteristic of modern capitalism its capacity to self transform through innovation.

4. Logistic laws of evolution

If Mansfield continued a tradition of growth dynamics that stretched back over half a century it is also the case that his "S" curve approach is central to subsequent work carried out by evolutionary economists. In this section I develop the idea that the "logistic law" is a defining signature of an evolving population, the dynamics of which is driven by a process of competitive selection. The connection is that Mansfield's work is in the context of populations of competing innovations and measures of their changing relative importance. In many cases the populations have simple structures, firms have adopted or they have not, a fraction of industry output is produced with a certain innovation a remaining fraction is not and so on. In each case the diffusion phenomena picks up on the changing structure of the population.

The defining attribute of an important class of evolutionary models is that they deal with populations of phenomena and they provide explanations of how the structure of those populations, as measured by the relative importance of the constituent members, changes over time. Populations of innovations are the basis of all diffusion models, even if the focus is upon a single technology or innovation there are always in the background one or more other technologies that are being substituted for. Indeed a wide number of diffusion models are in fact presented as models of technological substitution (Fisher and Pry, 1971; Kwasnicki and Kwasnicki, 1996; Mahajan and Muller, 1996). It is the fact that all diffusion processes involve more than one rival technology serving the same broad function that makes a population dynamics perspective relevant, even though the levels at which the population is defined may differ widely in each case. It is the population perspective which also gives rise to the importance of the "logistic law" as a fundamental characteristic of evolving population structures.

To sharpen the argument, we now define $x_i(t)$ as the absolute scale of utilisation of a particular innovation. We also define s_i is the measure of relative importance in the market of the ith innovation ($\sum s_i = 1$), and $X(t)$ is the overall scale of output of all the innovations in the market. It follows that the diffusion path for the scale of utilisation of any one innovation is the product of changes in its relative importance in the population and changes in the overall scale of the population. The first of these is dependent on the logistic law as we now show.

A general multi-innovation diffusion process is designed to explain how the relative importance of the different innovations, s_i, is changing over time. If $g_i(t)$ is the intrinsic rate of growth in the scale $x_i(t)$ at which the ith technology is utilized, then it follows that the motion of the population structure is governed by

$$\frac{ds_i}{dt} = s_i(t)[g_i(t) - g'_s(t)] \qquad (1)$$

where $g'_s(t) = g_X(t)$ is the average growth rate in the scale of utilization of all the innovations in the population such that $g'_s(t) = \sum s_i(t)g_i(t)$.

Now this relation is easily reformulated by defining $g_s(t)$ as the average growth rate in the utilization of all the innovations apart from innovation i, thus (1) can be rewritten as

$$\frac{ds_i}{dt} = s_i(t)(1 - s_i(t))[g_i(t) - g_s(t)] \qquad (2)$$

where $g_s(t) = \sum_{j \neq i} s_j(t)g_j(t)$, and the term in square brackets is the intrinsic diffusion rate for the ith innovation in this population.

Relation (2) is, of course, the general logistic law that governs the evolution of the population structure for this set of innovations. The saturation level for any dominant innovation is unity but the intrinsic rate of diffusion is not a constant. Notice that (2) captures the central feature of an evolutionary dynamic in terms of the distribution of the individual growth rates around the population mean; what is called the distance from mean population dynamic. Hence, the relative importance, diffusion, of any one technology depends on how the growth rate of its utilisation compares with the population average and this measure is continually changing during the diffusion process even for a fixed set of innovations. Note also that this diffusion rate can decrease as well as increase; the diffusion of a superior innovation always has in its background the decline in the relative importance of rival, and often "hidden" innovations.

If we now define $G_{is}(t)$ as

$$G_{is}(t) = \int_o^t [g_i(t) - g_s(t)]dt$$

then, on integrating (2) and imposing the initial condition $s_i(0)$, we can write the solution as

$$s_i(t) = [1 + A \exp(-G_s(t))]^{-1} \qquad (3)$$

with $A = (1 - s_i(0))/s_i(0)$.

Equation (3) summarizes the logistic law for this population, and it will be clear from relations (1) to (3) that the diffusion of a technology always follows the logistic law in terms of its relative importance in the relevant population. All

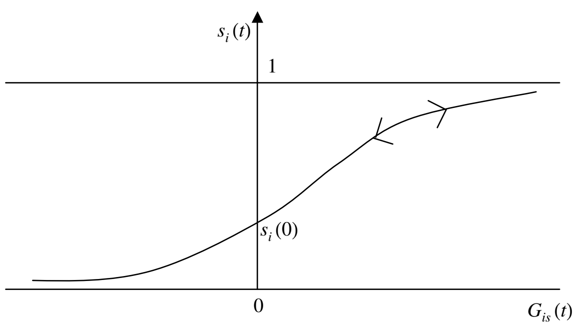

Figure 1.

the technologies in the population, therefore obey the general, reversible logistic diffusion mapping shown in Figure 1.

Provided that $g_i(t) > g_s(t)$ then $G_{is}(t)$ is increasing with time and so is $s_i(t)$. Conversely when $g_i(t) < g_s(t)$ then $G_{is}(t)$ is declining and with it $s_i(t)$. The important point to note is that the shares are not a logistic function of time, *simpliciter*, as in the usual logistic curve, but are rather a logistic function of the growth rate integrals $G_{is}(t)$. This is the logistic law which underpins all relative diffusion processes, reflecting the fact that diffusion is a problem in distance from mean population dynamics. Of course, diffusion in this relative sense is reversible, and it is typically the case that innovations once dominant in their field of application are displaced by the innovation of superior methods. This is what the logistic law allows for. This is a frequently observed phenomenon in diffusion and technology substitution analysis when say successive generations of an innovation are compared or when a sequence of rival innovations that are distributed over time is considered.[18]

Thus the logistic law captures the central principle of evolutionary analysis that populations evolve only in the presence of growth rate diversity and, ultimately, any theory of diffusion, like Mansfield's, is an explanation of that growth rate diversity. In his case the different growth rates are grounded in the relative rates of return to investment in different technologies, but many other sources of differential growth are possible depending on the innovations and the environment in which they are diffused.

Although the diffusion dynamics must follow the logistic law, as expressed in (3), it is not in general the case that the respective shares s_i trace a "naïve" logistic curve over time. The only case in which this is true is when we have just two innovations in the population and when their respective utilization growth rates are constants, for then $G_{is}(t)$ reduces to $(g_1 - g_2)t$. If $g_1 > g_2$, for example, then it is innovation one which follows the logistic curve of growth and innovation two the same logistic curve but in the direction of decline. Outside of this special case, the traditional logistic curve does not capture the evolution of any element in the population, although the underpinning logistic law always does. Matters are even more complicated and enriched when we allow new innovations to enter the population over time for then, if the entrants have superior growth rates, those established technologies formerly ascending the curve in Figure 1 will be pushed into reverse and may even be forced out of the population.[19]

The general point is, I hope, clear; while the diffusion process is always covered by the logistic law it is only in the simplest of cases that the time dynamics generate a "naïve" logistic curve. If this is true of the population structure, it is true *a fortiori* for the levels $x_i(t)$ at which each technology is utilized. Since the respective growth rates obey the constraint

$$g_{xi}(t) = g_{si}(t) + g_x(t) \tag{4}$$

it follows that the diffusion curve for X_i would only be a "naïve" logistic with respect to time if g_{si} follows the "naïve" logistic path and the overall scale of utilization, X, is constant.[20] An obvious counter example would be the diffusion of a particular set of technologies into a market environment that is growing at a constant rate. Then the dominant innovation would end up growing in scale in a non-logistic fashion towards an upper asymptote that is increasing at an exponential rate. To repeat, the fundamental importance of the logistic law does not imply the fundamental importance of the naïve logistic curve.

The final observation to be made is that the logistic law implies retardation in the evolution of the relative diffusion rates. When s_i is increasing it does so at a declining rate and when it is decreasing it does so at an accelerating rate. Thus, it is not surprising that Kuznets, Burns and others have found such impressive evidence in favour of the retardation hypothesis in terms of absolute scales of utilization. Whenever the overall population utilization rate $X(t)$ is changing slowly, then the logistic law does its work on the relative diffusion rates and imposes retardation on the utilization levels of the individual population components.

5. Concluding remarks

In this brief discussion of only a small part of Ed Mansfield's work we have focused on his exposition of innovation diffusion dynamics and sought to establish that it fits within a much wider tradition of evolutionary economic thought, one that stretches back to the early expositions of the logistic curve and theories of economic retardation and forward to modern evolutionary analysis. The connection should not cause the reader any surprise. Evolutionary change is change within populations and it occurs only when those populations contain economic variation within them. Deeply embedded in this dynamic of structural change is the logistic law and the related phenomena of retardation but we have seen that it is essential to distinguish between the logistic law and the naïve logistic curve. The later is a very special case and this in part explains why the logistic law may be consistent with a wide family of empirical "S" curves. By comparison, the logistic law is the signature of the evolutionary population dynamics and it follows from the nature of innovation and diffusion process in market economies. Much more important than the empirical realization is the economic explanation of the diversity in utilisation growth rates and the explanation of dynamic diversity as the fundamental evolutionary problem. Here we may find the connection between investment and diffusion that Mansfield emphasised and more generally the self transforming nature of modern capitalism in which innovation and its diffusion are of central importance. That is the value of Mansfield's legacy.

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Notes

1. See Geroski (2000) for an excellent, authoritative survey of the economics literature on diffusion and Mahajan and Peterson (1985) similarly on the marketing literature. Geroski draws attention to a wide variety of economic diffusion models, some based on processes of information spread, others based on equilibrium levels of diffusion that are disturbed by "interfering forces". *The Journal of Technological Forecasting and Social Change* is the premier source for work on diffusion interpreted in terms of technology substitution. The recent book by Geroski (2003) also provides important bridges between the more formal study of diffusion and work in strategic management. For other approaches to diffusion analysis see Antonelli *et al.* (1992) the survey by Lissoni and Metcalfe (1994) and Stoneman (1983, 1987). Pioneering work on the econometrics of logistic evolutionary processes may be found in Foster and Wild (1999a, b).
2. Mansfield (1971), p.178.
3. Mansfield refers to the work of Wilfred Salter (1961), who had developed a sophisticated account of the delay by firms in adopting new techniques based on Marshallian principles, but dismisses it on the grounds that it does not apply to regulated markets. Another important paper by Frankel (1955) on interrelated capital expenditures and investment in innovation was not, as far as I can ascertain, taken up by Mansfield.
4. Actually, the matter is a little more complicated, since a crucial assumption in restricting the Taylor expansion is that all terms of *second* order and higher in the current adoption rate are also dropped. Without this the adoption curve would not be a logistic. In typical, pragmatic fashion Mansfield justifies an apparently arbitrary restriction by claiming that adding a quadratic term for the adoption rate does not improve the goodness-of-fit of the investigated equations. See Mansfield 1961 reprinted in Mansfield 1968, p.139 footnote 10.
5. See the discussion in (Mansfield *et al.*, 1977), chapters 6 and 7.
6. In my own graduate work, undertaken in 1968, on the diffusion of three innovations in the Lancashire textile industry I had four names to turn to, Everett Rogers, George Ray, Zvi Griliches and Ed. Mansfield. Each had an enormous influence but, because the later was concerned with industrial innovations and the investment processes required to adopt them, his was the dominant influence on my own thinking (Metcalfe, 1970).
7. For an example see, Meyer and Ausubel (1999).
8. Of course, the same conclusion would follow if the underlying dynamics followed a Gompertz law or any other sigmoid law for that matter.
9. See Ireland and Stoneman (1982), Metcalfe (1981) and Cameron and Metcalfe (1988) for alternative specifications of this theme.
10. Nelson (1968) explores the same theme where the inelasticity of supply of an innovation reflects factors in the labour market.
11. Classic references are Arrow (1961) and Rosenberg (1982).
12. For further discussion see Geroski (2003). Metcalfe (2003) explores endogenous, diffusion induced technological improvement in the context of a Gompertz process.
13. From henceforth I shall speak of diffusion and adoption interchangeably, the interpretation being, I hope, clear from the context.
14. Ultimately, it emerged again, in different form in the idea of an industrial, technological or product life cycle in the 1960s. See Utterback (1994) and Klepper (2002) for relevant discussion.

15. In the logistic case the growth rate declines linearly with the scale of output, in the Gompertz case it declines log linearly.
16. Glenday (1938) applied Burns' method to long production series for eight UK industries and found consistent evidence of retardation.
17. It should be noted that Samuelson (1947, pp. 291–294) devoted a section of his *Foundations* to an analysis of the mathematical properties of the logistic curve but this had little subsequent resonance on the development of economic dynamics.
18. See the examples in Kwasnicki and Kwasnicki (1996) and Mahajan and Muller (1996).
19. Equation (3) is, in fact, closely connected to the Fisher/Price theorem in evolutionary dynamics, namely that population means of some attribute evolve over time according to the magnitude of the covariance of the attribute with the growth rates across the elements in the population. This theorem and its many sequalia play an important role in many formal evolutionary models (Nelson and Winter, 1982; Andersen, 1994; Saviotti, 1996; Metcalfe, 1998; Dosi, 2000; Witt, 2002).
20. In Mansfield 1961 reprinted in Mansfield 1968, the analogue to X(t) is the number of firms in the adopting population, which he takes to be constant-the given major firms.

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