Hors-série spécial 50 ans du BETA

1972-2022

DOCUMENTS DE TRAVAIL

« The economic dynamics of technologies development »

Auteur

Ehud Zuscovitch

Document de Travail – Hors-série n°2022-13

Juillet 2022

Notice introductive : **Patrick Cohendet**

BETA
Bureau d'économie théorique et appliquée

Site : https://beta-economics.fr
@beta_economics

Contact :
jaoulgrammare@beta-cnrs.unistra.fr

Notice d’accompagnement de l’article d'Ehud Zuscovitch, "The economic dynamics of technologies development" publié dans *Research Policy* en 1986.

Ehud Zuscovitch a profondément marqué l’histoire du BETA. Sa longue association avec le laboratoire remonte à la fin des années 70s lorsqu’après avoir obtenu un diplôme de technicien de production et étudié les statistiques à Tel Aviv, Ehud s’inscrit comme étudiant en sciences économiques à l’Université Louis Pasteur de Strasbourg. Participant avec passion aux différents projets de recherche sur l’innovation menés à l’époque par le BETA (notamment l’étude sur les retombées des programmes de l’agence spatiale européenne), et inspiré par de nombreux invités marquants qui ont séjourné au BETA à cette période (Georgescu Roegen, Keith Pavitt, Mario Amendola, Stan Metcalfe, Zvi Griliches, Giovanni Dosi, etc.), Ehud écrit en 1984 une thèse d’état lumineuse sur une approche méso-économique du progrès technique, où il défend l’idée que le développement de nouvelles technologies est fondamentalement un processus d'apprentissage localisé. L'innovation technologique a lieu d’après lui dans une structure particulière, un contexte spécifique de produits industriels et de processus de production qui se produit différemment selon les industries et dans le temps. Le processus est également, dans une large mesure, ancré dans l'histoire et doté d'un fort caractère d'irréversibilité qui le rend dépendant du chemin parcouru : le développement des technologies résulte d'un processus cumulatif d'ajustements successifs de la technologie à son contexte. Outre l'aspect localisé, le processus d'apprentissage comporte une dimension temporelle : si, pour une raison aléatoire, une trajectoire technologique donnée est sélectionnée, elle subira des améliorations successives qui la rendront plus performante, et renforceront ainsi ses chances d'être sélectionnée pour des applications futures.

Ehud valorise rapidement son travail de thèse dans cette première publication importante dans Research Policy en 1986 (« The Economic Dynamics of Technologies Development ») qui est à l’évidence une publication fondamentale qui a marqué l’histoire du BETA. Pour Ehud, l’approche schumpetérienne selon laquelle des technologies majeures spécifiques façonnent les vagues longues de l'activité économique, n’explicite pas suffisamment la manière dont se construit une technologie (on pourra noter qu’il fallait une certaine dose d’audace et de courage à un jeune chercheur pour critiquer ainsi l’approche schumpetérienne). En partant de la vision de Schmookler, qui avait théorisé le développement des innovations incrémentales, Ehud considère qu’une technologie spécifique apparait comme une unité théorique qui structure progressivement des innovations incrémentales selon une trajectoire cumulative. La dynamique générique propre à une technologie donnée naît d'un ensemble de connaissances et de savoir-faire. Le processus d'apprentissage à travers lequel ces corpus de connaissances sont progressivement construit fait que les innovations, au sens de solutions techniques à des problèmes, sont au centre du développement cumulatif des technologies. Cette vision de l'innovation comme une solution technique dans le processus de développement technologique implique la reconnaissance d’un statut spécial à l'unité fondamentale du processus, à savoir la réponse à la demande et à un problème spécifique à un moment donné du temps. Ce cadre théorique développé par Ehud Zuscovitch s’inscrit pleinement dans l’approche évolutionniste de Nelson et Winter (1982) pour lesquels le développement des techniques résulte d’un processus séquentiel et cumulatif marqué par des irréversibilités.

À partir de cette étape importante en termes de publication remarquée par toute la communauté des théoriciens évolutionnistes, Ehud va poursuivre ses recherches en analysant les conditions de création de surplus associées à l'innovation (en tant que création de nouvelles connaissances). Selon lui, ces conditions ont fondamentalement changé avec l'émergence d'un nouveau régime de croissance, qu'Ehud Zuscovitch appelle le "Système de Production Intensif en Information" (SPII). Alors que selon Adam Smith, l'allocation des ressources découle de la spécialisation (division du travail) et du surplus qu'elle génère, dans le nouveau régime des SPII qui explore le potentiel d'une variété infinie de produits rendue possible par la diffusion des TIC, Ehud Zuscovitch souligne que la génération de surplus dans ce nouveau régime de croissance provient principalement de mécanismes alternatifs dans lesquels la dimension coopérative est essentielle. Ehud Zuscovitch préconise que les nouveaux régimes appellent une organisation en réseau qui se surimpose au système de production avec une multiplicité de micro-marchés avec des spécifications particulières pour les petites séries. Il y a donc un nombre croissant de savoirs à maîtriser, et le seul accès possible à cette diversité est la coopération avec d'autres producteurs et utilisateurs des produits. Dans cette perspective, Ehud interpréte le rôle des entreprises dans le régime IPPS comme des conceptions institutionnelles qui assurent continuellement la correspondance entre deux structures : une structure formelle qui incarne la division du travail et une structure informelle qui exprime la division du savoir basée sur l'évolution des communautés de connaissances spécialisées.

En relisant ces travaux aujourd’hui, on peut mesurer à quel point le cadre du système de production intensif en information développé par Ehud dès le milieu des années 80, correspond à celui de l’économie de la connaissance qui deviendra le cadre de référence de l’économie de l’innovation dans les années 90. Au BETA, tout en poursuivant sans relâche ses travaux théoriques, Ehud s'est également lancé dans des recherches empiriques approfondies sur l'économie de l'innovation, qui ont abouti, entre autres, à des publications sur les matériaux avancés, et à une analyse fine des retombées du programme spatial européen, menée avec son doctorant, G. Cohen.

La personnalité bouillonnante et généreuse d'Ehud a joué un rôle central dans le développement du BETA. Il était un inlassable passeur de frontière qui est progressivement devenu indispensable pour assurer la cohésion entre les différents courants théoriques du laboratoire (notre collègue Teubal le définit avec justesse comme un « entrepreneur académique de premier ordre »). Ehud était également un maître dans l'art de diriger des thèses d'étudiants. Il savait fournir la bonne combinaison de conseils et d'indépendance qui a permis aux étudiants de développer leur plein potentiel tout en affinant l'orientation de leur travail.

Patrick Cohendet, juillet 2022.

The economic dynamics of technologies development

Ehud ZUSCOVITCH[1]

Bureau d'Economie Théorique et Appliquée (BETA), Louis Pasteur University, Strasbourg, France

There is little doubt about the fact that specific major technologies shape the long waves in economic activity. The trouble is that we don't understand very well what exactly is meant economically by the term specific technologies (synthetic materials, microelectronics and alike). The purpose of this paper is to set up a conceptual framework to fit this requirement and thus to understand the economic dynamics of the development process involved. Schumpeter did study the innovation's economics dynamics, still he did not elaborate a consistent story and the internal forces of a given technology. As for ourselves, following Schmookler by theorizing the behaviour of the small innovation (instead of the major one) and Rosenberg by taking into consideration the technical heuristic as such, we suggest a framework for the dynamics of technologies development. We use an evolutionary approach à la Nelson and Winter and gradually define the different components of this special dynamics. A specific technology would appear to be a theoretical unit which gives structure to elementary small innovations according to a particular cumulative path.

1. Introduction

In recent years, we have been facing a revival of the Schumpeterian tradition in the economics of technological change. In what can be termed the Neo-Schumpeterian approach, the technological interpretation of the process of economic development plays a major role. If such an interpretation is to achieve an acceptable degree of consistency, it has to contain as a core an explicit theory of the *dynamics of technologies development.* This requirement is acutely felt in the analysis of long waves. Only recently, Rosenberg and Frischtak [27] have set out some of the conditions for interpreting long-term fluctuations from the point of view of technology, stressing the cross-currents between economic sectors and successive time periods which characterize waves of innovation. These conditions are necessary but not sufficient. If we accept that specific technologies such as the railways, synthetic materials or electronics lend structure to economic activity, to the point of typifying actual developmental stages in the evolution of an economy, it is still important to know the internal dynamics of the process. Before tackling the

[1] I have benefited from discussion with J. Arrous, R. Ege, J.-L. Gaffard, J.-C. Guédon, P. Llerena, J. Mairesse, R. Nelson, K. Pavitt, G. Sensenbrenner as well as from remarks made by two anonymous referees. Remaining errors are mine. An earlier French article on the related work appeared in *Revue économique*, No 5, September 1985.

complex problems of how technology flows interact, it is necessary to define the way a single technology impinges on the economy. This is one of the aims of this article. By the end of this description, we will be in a position to introduce the concept of the generic technology and to indicate its proper- ties. This concept is designed to describe the ability of a given technology to supply, within a specific pattern, a set of economically valid solutions to a whole range of technical problems. A generic technology supplies the driving force be- hind a more complex array of technologies which we will call a technical System. The internal laws such a System follows will enable one to chart in technical and economic terms the performance of successive capital vintages arising from the emergence, maturing and decline of a particular technology System. A brief historical review of economic theories of technological change will serve to place our approach in context.

The theory developed by Schumpeter already contained the idea that the various stages of economic development can be explained by innovation and more particularly by the progress of technology (Schumpeter [31, 32]. However, it was not until the period of post-war economic growth and the work of Abramovitz [1], Kuznets [11] and Salter [28] that economists began seriously to study the relationship between technical progress and economic development, with the NBER conference [18] marking the true starting point of a major new line of research. Yet this period of rapid growth, along with the domination of macroeconomic modelling in the 1960s, gave rise to a theory of technical progress which treated it as a general and undifferentiated factor. Whether it be the "exogenous" technical progress of growth theory or the "endogenous" technical progress of Schmookler [30], we find in both cases that it is little more than an elastic term whose outwardly varied forms are regarded as exemplifying a single underlying law. It has taken economic recession, structural upheaval and the emergence of the "new technologies" for this concept of technical progress to be questioned. Only in the last few years have theorists such as Rosenberg [25, 26] or Nelson and Winter [20, 21] begun to incorporate the structural effects of technical progress into their economic theory. Technologies as entities of consistent organization of elementary innovations in-deed exert a considerable structuring pressure within and upon economic activity. This means we must move on from analysing technology *per se* and start to analyse individual technologies. Attempts to do so have already been made. Nelson and Winter [20] talk of the "natural trajectories" of technologies, while Dosi [5] suggests analysing "technological paradigms". Gille [7] and Freeman et al. [6] prefer to speak of "technology Systems", consisting of several basic technologies. Judging by the number and mixture of the variables brought into these different approaches, they are still embryonic. Real progress towards a description and analysis of the actual pathways of technological development requires more rigorous structuring and a more precise siting of technology and what it consists of in analytic terms. This is what we hope to come closer to in this article.

We shall do this in three stages centred roughly on innovation, technical progress and finally technologies themselves. In the first part we sketch the impetus which innovation gives to economic activity, and its cyclical nature. In the Schumpeterian construction we shall note the lack of a theory which would give structure to individual innovations and thus the technological foundations of the cycle dynamics. Theories of the diffusion of innovation represent an attempt in this direction. However, they are a first approximation which only scratches the surface, namely the reduction of uncertainty as an innovation is assimilated. This process needs to be rooted in a description of the dynamics of technological development, which in tum means determining the latter's main characteristics. This will lead us on to consider the nature of technical progress at a System level. From our investigations it emerges that a cumulative process drawing on a range of different innovative activities is the main feature to be contained in any theory of the dynamics of technological development. An outline of such a theory is given in the final part of the article.

2. Economic development and the diffusion of innovation

Economic analysis can be seen as a theoretical framework comprising two complementary aspects or forces: development (or creation) and adjustment (or regulation), each necessarily being coupled with the other. More exactly, during each cycle or fundamental unit of the economic development process[2] the two forces combine, with the mechanisms of development predominating during the upward phase of a cycle and the mechanisms of adjustment predominating in the down ward phase. Traditionally, it is adjustment which has been the focus of economic theory-making[3]. As a result, we already know something about the circumstances of adjustment (conditions of equilibrium existence, unicity and stability, although these conditions hold under very restrictive assumptions in highly simplified models). By

[2] The business cycle is to be understood here as the basic component of the process of economic evolution. A methodological observation cannot be avoided here. Long waves advocates and opponents argue a lot over the econometric validation of cyclical behaviour (of innovations, for instance). A business cycle analysis has first of all a theoretical task: to build a consistent theoretical framework for the process that governs economic activity between successive equilibria. It is just as if we validated, or just the same rejected, price theory on the basis of the observations as to whether equilibrium prevails or not.

[3] Adjustment theory is usually identified with resource allocation and loses much of its significance if it is not supplemented with a principle of surplus creation. Adam Smith's principle of Development is the division of labour inducing scale economies with every expansion. Marx's principle is labour surplus extirpation through capital accumulation and Schumpeter's is a chain reaction of triggering and induced innovation. We shall here explicitly deal with the latter, aware however that development, still poorly understood, combines all three principles outlined above.

contrast, our understanding of the mechanisms of economic creation is very limited. The trouble is that the positive meaning of the same concepts or the normative evaluation of the same facts is different in development and adjustment processes. For example - and this is typical - we find that features essential to an understanding of innovation and technological or economic development, such as uncertainty levels and external effects, are regarded in adjustment theory as “market failures”. In adjustment analysis, too, we are familiar with the connections between market structure and the optimum allocation of resources; but optimization cannot be defined in the same way for the purposes of analysing the development phase. The creation of new resources must inevitably come in part from a reallocation of existing resources, but the basic way in which resource creation works cannot be described in terms of perfect competition in a transparent market with full information. Creation behaves in essence like a special and transient form[4] of monopoly, reflecting a privileged access to information.

When creation comes into play, it enables a small but growing number of economic agents to make profits from the disparity between two price Systems, i.e. those prices set by the innovators and those set by everyone else. Towards the end of an economic cycle, such arbitrage will tend gradually to eliminate the profit margin by establishing a new System of information about quantifies and prices as the new base from which ail agents are operating. Attempts, therefore, to identify a market structure which favours innovation, amount to formulating a dynamic problem in static terms, since innovation is itself a process in which market structures are created and evolve.

The dynamic process described very sketchily above is at the core of Schumpeter’s view of the role of innovation in economic activity. More specifically, Schumpeter stressed the primordial part played by innovation in triggering each phase of economic development, i.e. each cycle. Once a cycle has been set off from the “ashes” of depression, business expands in waves of investment that encourage further innovation by providing better prospects of profit and thereby attracting more and more entrepreneurs. The whole economy is then irrigated by multiform and inter-industry technical progress, and a new redistribution of markets and market structures occurs according to the adaptiveness of firms and markets to the new technological regime.

Nearly 30 years separate the publication of his *Theory of Economic Development (Theorie der wirtschaftlichen Entwicklung)* in 1911 and *Business Cycles* in 1939. In the latter work, a broad theory of the dynamics of innovation forms the basis for a detailed analysis of actual cycles.

[4] It is transitory because, in order to benefit from this information, one must, at least partially, disclose it. Revealing the precise features of the new product is not necessary. Its mere existence is sufficient to induce the imitators’ efforts. In the case of a new process, growing market shares will indicate to competitors in which area they have to conduct their innovative efforts.

Without necessarily accepting an explanation in terms of innovation for Juglar and Kitchin cycles[5], one cannot deny that very long (Kondratieff) cycles are associated with the absorption of one or more primary technologies. The first long cycle is associated with the industrial revolution, involving the steam engine and the textile industry (1787-1842), the second (1843-97) with the railways, the third with electricity and motor vehicles, etc. (see Kuznets [11]). However, identifying each stage of development with a specific technology means that a general (non-specific) dynamics of innovation can no longer provide a sufficiently detailed and structured explanation of what happens. A more precise theory of these associations is needed. We must develop a much more precise and articulated theory on the temporal and structural relationships that make up the entity we call "specific technology". This is the gap which a dynamics of technology development should fill.

The first types of theory which can reasonably be interpreted as approximating to a dynamic model are those dealing with the diffusion of innovation. It is true that there are some elements in Schumpeter's theory which relate to diffusion, such as imitation, which plays an important part in the clustering of innovations. Schumpeter's analysis of diffusion, however, is unsatisfactory for two reasons. The process relies on an exogenously distributed entrepreneurship capacity, on one hand, and is subject to the rhythm of economic activity on the other. In fact, diffusion has an economic rational, so it has to be endogenously built. As for the rate of economic activity, it should of course be considered an exogenous variable.

In response to this need, specific theories have been developed to elucidate the internal logic of diffusion. However, they assume an unmodified innovation diffusing in an unchanging environment. This has led them to liken the diffusion of innovation to an epidemiological process, adopting the same sort of "mechanism" to explain the S-shaped curves followed in general by the development of individual industries (Mansfield [14]). For instance, the expanding number of people "infected" by an innovation (the users) is taken to express a gradual reduction in the uncertainties of employing it. The speed of the process is in tum explained by the returns afforded by an innovation and the investment needed to implement it. The positive point in this approach is that the learning in the aggregate of potential users is achieved through interaction. Interaction among agents or externalities is the very heart of the diffusion process. Although the working hypothesis which has thus been constructed to account for the diffusion of an innovation through the pool of potential users gives good results upon econometric verification, some interrelated

[5] I don't think one can easily follow Schumpeter and accept the innovation cause for the "Juglar" and the "Kitchin" cycles. In the nineteenth century, the Juglars were surely linked to the gold standard and the associated economic policy more than to anything else, and very probably Keynesian macro-monetary economic tools have "straightened" them up.

shortcomings remain. The Mansfield model of diffusion is an inter-firms model, so that implicitly the population of potential users is homogenous, and every individual firm “chooses” whether or not to adopt the innovation. Industry is not homogenous either in size or in its required minimum rate of return on adopted innovation. Davies [4], in a comprehensive work on process innovation, constructed a diffusion model based upon these heterogeneities. It remains nevertheless an inter-firm model. Yet, if size is such an important factor in the decision making process of whether or not to adopt the innovation, that is because the size of a firm enables large ones to fix more precisely the level of introduction of the new piece of equipment as a part of ail capital. This in tum implies both an intra-firm approach and an explicit decision-making algorithm allowing for the revision of expectations as learning progresses (Stoneman [34]). But diffusion does not depend entirely on the “users” of an innovation; the process is often one of interaction between buyers and sellers, mediated by the market. This interaction ultimately determines the price of an innovation. Consequently, the very way in which the price of an innovation is first set and then changes has the effect of sharing the returns on using it between both producer and “consumer” (Metcalfe [16]).

3. A System view of technical progress

Although a microeconomic background has now been provided for an analysis of diffusion, along with a first approximation to a dynamics of technology, we should not forget that diffusion does not involve an unchanging innovation in a constant environment. As an innovation is created and assimilated, it is in reality successively modified by the process of industrial learning in all its aspects: R&D, learning from experience (learning by doing, learning by using) (Arrow [2], Rosenberg [26]), engineering design, organization and methods, etc. A deeper perception of technical progress and a recognition of the role of technologies in creating new structures, must take us be- yond an analysis of the diffusion of separate innovations. We need to deal with the spread of the innovation process itself as it affects the evolution of industries and technologies. But once we leave the microeconomic sphere and try to take a System view of technical progress, there is a choice of method to consider. The investigation here will approach the subject from two different directions. The first, which we will call the synchronic or horizontal axis, is to analyse the structural disparities attributable to the innovation process as evidenced in the State of industries relative to each other. Such disparities exist within the economy at any given time and are probably the source of the differential productivity puzzle (Nelson [19]). The second axis, which we will call diachronic or vertical, involves studying the forces which mould technical progress over time. To borrow an analogy from evolutionary theory, one could say that the first axis deals with a cross-section of innovation “species” while the second addresses the selection pressures operating

on these species.
The horizontal or synchronic approach is by nature static, concentrating on the pattern of leads and lags which characterize the industrial fabric at a chosen point in time. Using relatively simple regressions rooted analytically in production functions, several studies have established significant links between innovative effort, normally measured in terms of research and development, and the performance of firms, which is usually measured in terms of productivity. They have identified disparities between sectors which support the general proposition that investment in R&D brings gains in productivity. Some parallel research has looked at the structural breakdown of R&D to obtain a more discriminating picture of the process of industrial innovation. Comparisons have been made, for example, between regression analyses based on R&D spending and on the number of personnel assigned to R&D (Leonard [12]). He found, for instance, that R&D expenditure over net sales is a better indicator than the proportion of scientists and engineers in total manpower for practically ail performance indicator such as sales, assets, net value, real output, etc. (except for productivity, where the labour indicator gives better results). In a different area, various authors have tried to isolate the relative contributions of fundamental and applied research (e.g. Mansfield [15]) or to compare public sector R&D. One of the main benefits of these lines of investigation has been to bring out the difficulties inherent in these kinds of measurement and analysis and hence the implications for assessing the role of R&D (Griliches [8]). It has been shown, for instance, that in measuring R&D much depends on choosing a representative variable. In particular, it has emerged that using data on the commitment of resources to R&D does not produce the same results as do comparable evaluations based on counting new patents (Pavitt [22]).
These divergent results highlight a major and fundamental problem. Establishing a regression between R&D and productivity is inspired by the central idea that innovative effort is an important source of enhanced performance in an industry, something no-one would dispute. However, it does not follow that R&D investment *as such* is an unbiased estimator of the innovative effort under question. In reality, each industry is built on a particular mix of innovative activities ranging from fundamental research to learning by experience, with many different ways of producing and spreading endogenous technical change in between. As different forms of economic appropriation are associated with different innovative activities (Levin et al. [13]), it follows that there is no single performance estimator (such as productivity, net worth, assets and so forth). Thus, R&D- productivity regressions are biased on both sides. Since each innovative activity is basically associated with a different kind of commercial assimilation, the pathways taken by different industries as they evolve cannot be obeying a single law of development.
A second criticism to be made of correlations between R&D and productivity is that they do not take explicit account of the interplay between innovations in different

sectors (or interindustry technology flows). A sector's own innovative effort is not sufficient to explain its level of productivity (given the other classical factors of capital and labour). The economic performance of an industry depends on a complex pattern of technology transfers. Some industries can themselves generate the technical advances they need whereas others have to import them from outside. Different diffusion rates, externalities and spill over mechanisms make intersectoral technical change even more heterogeneous. Again we see that the variety of innovative processes is due to different logics of development and not a single law.
A third criticism would query the causal link implicit in using intersectoral disparities in R&D investment to explain intersectoral disparities in the performance of industries. To put it in very simple terms, it is supposed that the greater the R&D effort, the better the performance. While it cannot be denied that a major R&D effort will overall bring improved performance, this can never be turned into a general recipe for strategy, whatever the sector concerned. It is doubtful whether the profitability of the leather industry can be increased very much by a large amount of endogenous R&D. The fact that there are leads and lags in R&D and performance between different industries at one and the same time would indicate that there exist many development opportunities, the most significant of which will at- tract the funds available for R&D (Salter [28]). So the leads and lags of industrial cross section observations cannot be explained by different R& D. Both R&D variables and productivity, ail things equal, simultaneously react to development potential. The next step, therefore, is to identify what these "potentials" consist of; in fact they represent the ability of particular technologies to provide *specific* solutions to technical problems related to the satisfaction of needs.
The conclusion from ail three criticisms is that features specific to different sectors should not be used as evidence for a single factor influencing performance or for a single law of development. Instead, sectoral peculiarities must be understood in terms of several explanatory models grouping economic and technological variables according to different development strategies that are consistent within themselves. This does not mean we should switch from the idea of a single underlying developmental law to considering a host of individual cases, but that we must identify a few basic patterns. On the basis of statistics on innovations introduced between 1945 and 1980, Pavitt [23] puts forward, by way of example, three main patterns to describe the pathways followed by firms according to the origins of their technologies:

- firms whose technology depends primarily on advances in science (such as Chemicals and electronics);
- firms which depend on other industries for their technology (and normally buy their machinery with embodied innovations from them, such as the textiles and leather industries);
- firms which themselves develop the technologies they require (firms with

relatively endogenous technical progress). These can be continuous- process industries with high capital intensity, such as metal production and shipbuilding, and they can be lighter and more specialized industries such as mechanical engineering and instrument-making.

These three patterns account well for groups of behavioural variables such as the way in which R&D effort is exploited, the scale of production, relations with suppliers and customers etc. An analysis of them, however, calls for a more detailed theory. In my own one, the specific technologies are those which give structure to industrial configurations and are, in a way, the more elementary building blocks. In order to be able to build typical patterns and to study their evolution, we need to go deeper and define those building blocks first. For that purpose, however, a purely synchronic view is not sufficient. If industrial and technical specialities are organized in particular configurations it is due indeed to a *process* that brought them together. A purely synchronic approach is not enough for that purpose; the time dimension also has to be taken into account.

A diachronic or vertical analysis of the long- term evolution of technical progress once again faces us with several difficulties. To recall the vertical (or diachronical) analysis of technical progress is basically the study of the economic forces acting on a certain variety of innovations to give them momentum in some *directions.* The most traditional among theories entering this category of analysis is innovation induced by factor-price changes. There is no doubt that major factor-price changes, such as wages or energy price, induce technical progress that will lead us to substitution of a relatively expensive factor by another one. Yet, increased mechanization to substitute labour is not a very fine selection tool since it is possible to reach the same goal in many ways. A similar criticism applies to the attempts to explain technology development by a pure demand-pull approach (Schmookler [30]). Of course, demand intensity drains innovation activity to those fields where the same effort will yield more money just because the related activity is larger. Still it does not help us in our search for a satisfactory concept of specific technology. Even those empirical analyses which show that the identification of a need by the innovator is a crucial variable in accounting for the success of a particular innovation (analyses which, by implication, support the demand-pull hypothesis) have done no more than demonstrate *ex post* that a demand existed, and have not provided the analytical tools to explain why an innovation succeeds in some specific directions. In sum, such studies have mainly produced descriptions and very little in the way of explanation[6]. The need for a precise analysis of the interactions between economic

[6] An interesting point arising from this argument about supply and demand and their impact on the long term is that it serves to underline how little we know about the process of information exchange and the types of trial and error which go on as an abstract need is successively transformed into a commercial product with particular characteristics (Teubal (35]).

agents on both the supply and the demand side has been clearly shown by Mowery and Rosenberg [17].

In its present state of advancement, the analysis of long-term changes in technical progress should be less ambitious and look for a lesser degree of determination. Otherwise stated, their influence is exerted within existing development potentials. What is then the temporal process which limits such potentials? The answer to this question is contained, I believe, in the evolutionary approach developed by Nelson and Winter [21], in which the development of techniques appears as a sequential process. This approach is able to include the main mechanisms by which innovations diffuse, whether internally (through the growth of a firm) or externally (by imitation). More crucially, however, it is consistent with the cumulative way in which technologies develop because it takes into account the irreversible nature of decision-making, particularly as regards the choice of techniques (see also David [3]). Contrary to the usual representation in economic theory, technologies which have been left unexploited in the past cannot be taken down again from the shelf at a later stage. If technologies were selected at any given time from the same range of choices, the consequences of a less-than-optimum choice based on uncertainty and imperfect information would be relatively slight since it would always be possible to tum back the clock, as it were, and pick out again the best technology for a given configuration of economic variables. In this case, by the way, there would be no fundamental difference between neo-classical maximizers and bounded rationality theoreticians, the former simply admit- ting the latter as an acceptable approximation with no serious gap. On the other hand, if techno- logical options are mutually exclusive, then "sub- optimality" is *cumulative* and specific patterns are necessarily created.

In reality, the chosing of technologies is a process similar to cumulative drift and has a characteristic element of irreversibility. The immediate argument for this interpretation is that every decision taken by a firm affects the structure of the way it operates by imposing a direction on its investment, work organization, staff skills and so on. In other words, technical progress does not take place in an infinitely flexible environment. There is a second reason which is even more important because it relates to the economy as a whole. If particular technologies are not adopted at a given moment in time, they will tend to disappear and cease to be available when future choices have to be made, even though, retrospectively, they appear optimal in the economic situation in which the choice becomes necessary. Knowledge (or know-how) that is divorced from practice will tend to lose its availability even if it can still be reconstructed from artefacts or documents. Technologies are continuously evolving, with modifications being made to them all the time, so that the system as a whole progresses; but knowledge which is not applied in practice drops out of this evolutionary process and becomes more and more expensive to reactivate.

4. The process of technology development

The limited explanatory power of the horizontal and vertical approaches suggests that the type of explanation should be changed, as well as indicating the direction of this change. The central proposition to emerge from our horizontal analysis is that the multitude of innovative activities cannot be reduced to R&D alone and that each technology and industry rests on a particular combination of innovations. The central proposition from our vertical analysis is that technical progress is basically cumulative in nature. In point of fact, these two propositions complement each other and simply represent two different ways of regarding the same process. Stated in dynamic terms, technology development is a cumulative process drawing on a whole range of innovations. In "topographic" terms, we need to go beyond our horizontal approach and consider the development potential of technologies, which first opens up and then fades away. We must also shorten the horizon of our vertical approach to the medium term and take account of the mechanisms by which specific factors accumulate to create the development potential.

If we accept this description of the process of technology development, we need to pursue the analysis in order to get at its technical core. To achieve this, we propose distinguishing three different aspects. Technology development can be broken down into three fundamental dynamics which interact and together determine the path-ways which technology development will take. These are the generic dynamic, the industrial dynamic and the inter-industry dynamic.

- The generic dynamic is the inherent dynamism of a given technology. It derives from the capacity of its body of knowledge to supply technical solutions that can be used by the productive System. As examples one could cite the seminal role of mechanical engineering and electronics. Later in the article, we shall study its structure in detail.
- The industrial dynamic. Firms which participate in the development of a technology also develop themselves in the process. A successful innovation will increase profitability and competitiveness in firms that have been involved in the R&D leading to the innovation. Performance is improved directly through an in- creased sales volume from new products and processes. It is also improved indirectly through the learning process which enriches the know-how resources of the firm. This is expressed in the current value of the firm as measured by its share price (or more generally on the capital market). In the course of this process, a firm will display the classic signs of industrial development: expansion, profits, economics of scale, etc. However, it is possible to analyse the industrial dynamic more or less separately from any technology effect. For instance, suppose that demand rises in a traditional sector (e.g. an increase in the consumption of synthetic

rubber for making tyres because of a war in another country); the firms involved will tend to develop with the usual symptoms of industrial development.

- The inter-industry dynamic. A given technology will also develop under the influence of technical advances in related fields. Computer technology, for example, has benefited from progress made with new superconductor alloys. Of course there is a relationship between the interactive dynamic and what we have called the generic dynamic. If a promising commercial potential arises in computer technology, this field will soon start to "attract" technical advances made in other fields. However, the interactive dynamic is amenable to an initial analysis on its own account, regardless of whether there is a generic principle to unify and give sense to the grouping together and development of individual innovations. Thus, even if we imagine innovations arising in a purely random way in different industries, there will still be cross-currents affecting technical progress as a whole[7].

Let us simplify matters by leaving aside the industrial and the inter-industry dynamics and concentrating in detail on the cognitive heart of technology development dynamics, namely the generic dynamic[8].

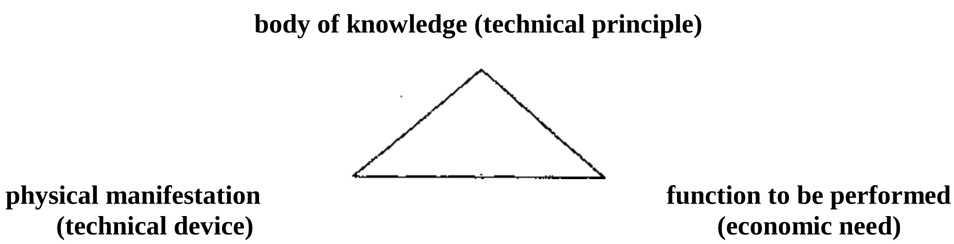
The generic dynamic peculiar to a given technology arises out of a body of knowledge and know-how. The learning process by which such bodies of knowledge are built up means that innovations, *in the sense of technical solutions to problems,* are at the centre of the cumulative development of technologies. This view of innovation as a technical solution within the process of technology development is not neutral. It implies that we are attributing a special status to the fundamental unit in the process, namely the response to a specified problem at a given point in time. From the outset, we will opt for a progressive setting in which the technical solution that the innovation represents is evolving. There may have been a scientific principle that was instrumental in giving birth to the technical principle, or it may have been more the result of experiment. In itself, it does not even exclude the possibility of an upstream predominance of a scientific principle or even of a possible *ex ante* major innovation that triggers the process, although much more often than not, major innovation is an *ex post* terminology *{ex post major*

[7] Many attempts have been made to identify dynamic movements in the exchanges between industries in order to assess the relative contribution of each sector to "driving" the System as a whole. Such analyses have remained only partially successful because the share of innovation in the totality of these exchanges is not necessarily very large. Sherer's work [29] on intersectoral technology flows has been a major step forward in this line of investigation. Different methods for the same problem have been suggested by Siniscalco and Mimighano [33] and Zuscovitch et al. [38].

[8] However, in order to obtain real patterns in technological development, one has to combine elements from the three families of dynamics above.

innovation being merely the recognition that a specific technology had powerful heuristics shaping economic activity and this is precisely what we are trying to make endogenous here). Actually, whether the precise starting point of a given technology is triggered by a "big bang" or not is of no real importance. In either case, the development of a technology is best seen as a succession of technical solutions. The main argument for this evolutionary dimension is that a technical solution has a concrete and tangible side deriving in part from existing material constraints. Hence the evolutionary aspect is inherent in whatever physical device is finally installed. Every technical solution is embodied in a technical de- vice which is, at least partly, a capitalization of previous technical solutions (whether from the same technology or not). In analysing the generic dynamic and the body of knowledge associated with it, we can proceed in two stages: first of all studying the structure of the fundamental unit, i.e. the technical solution, so as to identify the economic constraints that operate on it continuously, and only then considering the evolution of bodies of knowledge themselves.

The structure of a technical solution can be represented as a triangular relationship between three basic elements:



We start with a technical function to be performed (e.g. transmission of movement, bonding propulsion). This function corresponds to an economic need or, put another way, a value is attached to solving the problem. Depending on how far a technical problem is broken down into its detailed components, the degree of precision in defining the function to be performed will be greater or less. The function is a technical "space" within which a variety of solutions will fit (e.g. bonding can be by glueing, riveting or welding).

The second component in arriving at the solution is the primary knowledge and know-how applied to finding the solution. Let us call it the "body of knowledge". Sometimes this will be a scientific principle (a principle of electronics, chemistry or mechanics for example) but in many fields there will be no general law underlying the solution and the only proof that an idea will work comes from experiment (as in aerodynamics, for example)[9].

Finally, the chosen technical solution will take on a particular physical form. The response to the problem is incorporated in a piece of equipment. This physical manifestation will involve other industrial specialties (if the solution is a laser source, for example, this implies mastery of automation, electronics and optics).

This way of dissecting how a technical solution is arrived at has the advantage of clarifying the economic constraints on the development of a body of knowledge through successive stages. Let us look first at the relationship between the body of knowledge and the function to be performed. Each body of knowledge has its own topology that is relative "distances" between alternative technical solutions. This is exactly what Nelson and Winter [20] mean when they talk of the natural trajectory of a technology. At any given moment, the pattern of demand and the structure of relative prices act to select among the possible technical functions to be performed and can thereby favour or hinder the development of a body of knowledge. Within this web of relation- ships, we can assume that the economic constraints are sequential because the pattern of demand may vary more or less independently over time[10].

The physical manifestation of a solution also imposes a constraint on the development of a body of knowledge. A technical principle, the essence of a body of knowledge, must always be translated into a technical device. In technological practice, the resources at the disposal of an engineer are defined as much by the related technologies incorporated in the device as by his immediate body of knowledge. The technical solution must above ail work, and consequently be based in part on existing products. The latter themselves represent the end-points of a long pro- cess of experiment and learning. Accordingly, the constraints exerted by the equipment on a body of knowledge are cumulative. What this means is that the resources available for innovation are inevitably restricted. Hence, as soon as a certain pathway has been chosen in the form of a succession of artefacts (or more

[9] Particular ways of problem solving have sociological foundations and sociologists of science have often emphasized the role of professional schools in forming a pattern of scientific behaviour (engineering schools too are merely standardisation instruments for specific ways of problem solving).

[10] Two remarks ought to be made at this point. First, demand or relative prices are not the only signals that select relevant problems that have to be solved. Purely technical and organizational reasons such as production bottlenecks play an essential role in selection, as Rosenberg emphasizes in a large number of his writings. (Still, important relative price changes give an edge to some technologies rather than to others.) The second observation is that the sequential economic constraint (or the independent demand structure, at different times), does not imply that the various available bodies of knowledge have at every sequence a resetting of their chance to survive. However, this is due to the different stages of development of the different bodies of knowledge and we shall deal with that later on.

generally a series of physical manifestations) it means that other paths will never be followed even if another trajectory would have been better to achieve a particular solution. Take as an example two bacteria: A, which is able to produce insulin, and B, which is able to digest oil slicks at sea. Assume we have domesticated A. This means we now know a collection of ways in which it will "work" as a piece of "equipment", as the result of massive investment in R&D. If a need then arises for the function performed by B, we can cut out the relevant gene and insert it into the genetic make-up of A and use A to do the work of B. Had we known how to set B to work directly it is likely that this would have been more efficient and thus more economic. The problem is, of course, that society has already invested in a particular set of goals and that this investment has had a cumulative impact[11].

We have, so far, apprehended the economic constraints *within* the structure of the technical solution. We have thus isolated the purely technical element (the relevant technical topology or "technological trajectory") from its economic components for any given moment. As far as the elementary unit is concerned we have reached the limit of the field where economies are applying. Schumpeter, in his history of thought, has already observed that when on one side we have an economic variable and on the other one which is non-economic, we have reached the frontier and should stop. It remains now to outline some of the dynamic features. In describing the evolution of a body of knowledge, one might try to define its developmental stages (emerging, maturing, declining), as applied to "ancestral lines" (see Maunoury [15a]). One might also try to establish the "mechanics" of the development of a body of knowledge by speaking, as Dosi [5] does, of "technological paradigms". It seems to us that it is important first to understand how the transition from one technical solution to another is accomplished, which in fact encapsulates the problem of industrial learning and innovation. More particularly, it is necessary to elucidate the role of imitation as a non-trivial procedure. It appears that, at first, there is usually an attempt to make an innovation perform in the same way as the superseded product, technique or material. The untried is quite simply substituted for the tried. In point of fact, this approach to technological learning has a straightforward economic rationale. By requiring the new product to do the same things as the old product or process, it is possible to conduct an easy cost-benefit analysis[12]. As learning progresses, however, it is discovered that the innovation has new properties. A whole new generation of processes and services then becomes conceivable. There are many examples in the "new technologies" (e.g. composite

[11] It should perhaps be pointed out that this cumulative constraint ought not to be regarded as a total inertial barrier. The development of modular approaches, i.e. interchangeability, has been designed precisely to get round this evolutionary constraint. On this subject see Rosenberg [24] and Guédon [9]. For an analysis of the cumulative process and its properties, see David [31].

[12] However, it is sometimes technically absurd since we are asking the new principle to be compatible with a series of technical constraints that were made to suit technically something else

materials, machining lasers, computerized process control) which confirm this learning principle[13]. As learning progresses, it is accompanied by a stimulation of the market and very often by an accelerating process of standardisation and scale economies follow. The exploitation of the new properties tends in its tum to become standard, to become a method distilling and engineering approach, and to predetermine the way new technical problems are tackled. Engineering practice is of course the most powerful tool for the diffusion of technical solutions. The capacity or the vitality of a given body of knowledge grows with methods but at the same time sets a limit upon the adaptive capacity of the technology. Decline is not yet there, but limits of the "territory" are in sight, signalling new openings for new principles. We have made some exceedingly simplified short cuts into the development principle of a body of knowledge. This is due to our uncertainty and lack of knowledge about some of these issues. Our understanding of the economic constraint on the evolution of the body of knowledge requires substantial work that remains to be done. An economic theory about the engineer's role is needed at this point.

5. Conclusion

In a series of approximations, we have sketched a description of the dynamics of technology development and tried to define its central principle. It has been an attempt only, of course, and all the features we have included need to be more closely interwoven. Our approach has been one of straight analysis; as the classification of technology development is consolidated it should be possible to produce a better synthesis and to point to actual technology pathways combining the different categories of dynamic in specific configurations.
Nelson and Winter [20] have defined the central problem of constructing a theory of technical progress as follows:

[13] Very often the novelty will reveal its economic potential when the structure of the technical solution is reconceived in order to take advantage of its intrinsic properties. Composite materials are usually introduced to combine strength and lightness. Such considerations are particularly important in the aircraft industry which already makes intensive use of these materials. For several years now, helicopter rotor blades have been made with composites rendered artificially heavier with metal charges (because of security). The reason is that it has been shown that the relevant sort of composites practically does not wear out (fatigue), so they do not have to be replaced every 1000 flying hours or so, as does their metal equivalent. In the car industry, a constructor has considered producing a particular pièce of machinery with the help of a laser tool. When the same processing rule as its mechanical equivalent was followed, it was not cost effective. When the same piece was decomposed into three pieces welded with a laser, there was a 50 percent cost reduction. Many other examples are following the same principle. It is only when the designer reconceives the solution with the help of the new principle that a real diffusion of the latter may take place in the form of a series of new products and processes

> ...The weakness of present understanding of the reasons behind the differential growth puzzle is in part due to lack of facts. But it is due at least as much to lack of theory that will enable us to knit together and give structure to what we know and extend our knowledge beyond particular facts. While there has been a considerable volume of research by economists, other social sciences and historians of science and technology, that ought to bear on the differential productivity puzzle, that research is not well connected. This makes review, much less integration, of what is known quite difficult. More important, it means that knowledge is in the form of congeries of semi-isolated facts, rather than a connected intellectual structure...

At the close of a step into the research work whose theoretical skeleton has been reported in this essay, it seems to us that its main contribution would be to advance a little in the direction traced by this quotation. The emphasis we have put on the interactive nature of technical progress has made allowance for some integration. We have distinguished among "classes" of interactive phenomena within general innovation dynamics. While approaching more and more the hard core of technology, economically speaking, we have associated variables in quite well defined explanation mechanisms. These mechanisms seem to have reasonable internal coherence and at the same time to be quite different from one another (not excluding interdependence, of course). These classes of dynamics are necessary to technical change, much in the same way we distinguish, for instance, between business cycles and structural analysis or, at a more fundamental level, between macro- and microeconomics. It is certainly not a wholly consistent structure. Besides the experimental nature of our explanation, we fear that the phenomenon of technical change does not lend itself to further structurization. This may be due to the unavoidable interdisciplinary dimensions of this particular field of research. The diversity of innovation activities will certainly remain the most important feature of the process. Ail that one can possibly do is to bring more theoretical consistency. We are hoping this has been achieved here, at least partially, in the form of a conceptual framework for the process of technologies development.

References

[1] M. Abramovitz, Resource and Output Trends in the U.S. Since 1870, *American Economic Review,* (papers and proceedings) (May 1956) 5-23.

[2] K.J. Arrow, The Economic Implication of Learning by Doing, *Review of Economic Studios* (1962) 155-173.

[3] P.A. David, *Technical Choice, Innovation and Economic Growth* (Cambridge University Press, Cambridge, 1975).

[4] S. Davies, *The Diffusion of Process Innovation* (Cambridge University Press, Cambridge, 1979).

[5] G. Dosi, Technological Paradigms and Technological Trajectories, *Research Policy* 11 (1982) 147-162.

[6] C. Freeman, J. Clark and L. Soete, *Unemployment and Technical Innovation* (Frances Pinter, London, 1982).

[7] B. Gille, *Histoire des Techniques* (Gallimard, La Pleiade, Paris, 1978).

[8] Z. Griliches, Issues in Assessing the Contribution on Research and Development to Productivity Growth, *Bell Journal of Economics* (1979) 92-116.

[9] J.-C. Guedon, From Unit Operations to Unit Processes, *Chemistry and Modem Society* (American Chemical Society, Washington, 1983).

[10] A.B. Jaffe, The Effects of Market Demand, Technological Opportunity and Research Spillovers on R&D Intensity and Productivity Growth, NBER Workshop, July, 1984.

[11] S. Kuznets, *Economic Change* (Heinemann, London, 1954).

[12] W.N. Leonard, Research and Development in Industrial Growth, *Journal of Political Economy* (March-April, 1971) 232-256.

[13] R. Levin, A.K. Klevorick, R.R. Nelson and S.A. Winter, *Survey Research on R&D Appropriability and Technological Opportunity, Part I* (Yale, University, New Haven, CT, July 1984).

[14] E. Mansfield, Technical Change and the Rate of Imitation, *Econometrica* (October 1961) 741-766.

[15] E. Mansfield, Basic Research and Productivity Increase in Manufacturing, *American Economic Review* (December 1980) 863-873.

[15a] J.L. Maunoury, *La genèse des innovations* (PUF, 1968).

[16] J.S. Metcalfe, Impulse and Diffusion in the Study of Technical Change, *Futures* (October 1981) 347-359.

[17] D. Mowery and N. Rosenberg, The Influence of Market Demand Upon Innovation - A Critical Review of Some Recent Empirical Studies, *Research Policy* 8 (1979) 102-153.

[18] NBER (National Bureau of Economic Research), *The Rate and Direction of Inventive Activity*, Proceeding of a Conference (Princeton University Press, Princeton, NJ, 1962).

[19] R.R. Nelson, Research on Productivity Growth and Productivity Differences: Dead Ends and New Departures, *Journal of Economic Literature* (September 1981) 10291064.

[20] R.R. Nelson and S.G. Winter, In Search of Useful Theory of Innovation, *Research Policy* 6 (1977) 36-76.

[21] R.R. Nelson and S.G. Winter, *An Evolutionary Theory of Economic Change*

(Belknap-Harvard University Press, Cambridge, MA, 1982).
[22] K. Pavitt, R&D, Patenting and Innovative Activities: A Statistical Exploration, *Research Policy* 11 (1982) 33-51.
[23] K. Pavitt, Patterns of Technical Change: Towards a Taxonomy and a Theory, *Research Policy* 13 (1984) 343-373.
[24] N. Rosenberg (ed.), *The American System of Manufactureing* (Edinburgh University Press, 1969).
[25] N. Rosenberg, *Perspectives on Technology* (Cambridge University Press, Cambridge, 1976).
[26] N. Rosenberg, *Inside the Black Box: Technology and Economics* (Cambridge University Press, Cambridge, 1982).
[27] N. Rosenberg and C.R. Frischtak, Technological Innovation and Long Waves, *Cambridge Journal of Economics* 8 (1984) 7-24.
[28] W.E.G. Salter, *Productivity and Technical Change* (Cambridge University Press, Cambridge, 1960).
[29] F.M. Scherer, Inter Industry Technology Flows and Productivity Growth, *The Review of Economics and Statistics* (September 1982) 627-634.
[30] J. Schmookler, *Invention and Economic Growth* (Harvard University Press, Cambridge, MA. 1966).
[31] J.A. Schumpeter, *The Theory of Economic Development,* (Oxford University Press, Oxford, 1961) (1st English edn. 1934). Originally published as *Theorie der Wirtschaftlichen Entwicklung* (1911).
[32] J.A. Schumpeter, *Business Cycles* (McGraw-Hill, New York, 1939).
[33] D. Siniscalco and F. Mimigliano, Technology and International Specialization, *Banca Nazionale del Lavoro Quarterly Review* (September, 1984).
[34] P. Stoneman, Intrafirm Diffusion, Bayesian Learning and Profitability, *The Economic Journal* (June, 1981) 375-388.
[35] M. Teubal, On User Need and Need Determination: Aspects of the Theory of Technological Innovation, in: M. Baker (ed.) *Industrial Innovation:* Technology, Policy, Diffusion, pp. 226-289 (Macmillan, London, 1939).
[36] S.G. Winter, Satisficing, Selection and the Innovating Remnant, *Quarterly Journal of Economics* (1971) 237-261.
[37] E. Zuscovitch, *Une approche méso-économique du progrès technique. Diffusion de l'innovation et apprentissage industriel*, thèse de doctorat d'Etat, Strasbourg, 1984.
[38] E. Zuscovitch, J.P. Auray and G. Duru, Incremental Innovations, Industrial Partnership and Public Policy, Paper presented at a Conference on Innovation Diffusion, Venice, March, 1986,