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# *Technical Progress and Structural Change in the Process of Economic Development* *

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## Introduction

Economic development is, in essence, structural change. The latter if it is to be of a progressive kind requires, in turn, progress in modes of production. Historically, evolution from mostly agriculture based economies, mainly producing necessities, to full fledged industrial systems has brought about steadily rising productivity. Before systematic growth occurred, however, such economies appeared as a set of necessarily integrated activities, even if at very low technological levels. Traditional agricultural economies are, in fact, denoted by processes in which single units carry out all the stages of production keeping exchange at a minimum. Intermediate inputs as well as durable means of production are directly produced by peasants or by village units strictly operating in a very narrow economic territory. This mode of production was radically transformed by the division of labour.

In Adam Smith's classical analysis, division of labour is a consequence of the development of an exchange network and therefore of capital accumulation; it is also its prior condition, however, since productivity increases which result from it allow a greater surplus and thus larger accumulation. Smith's theory is, in this sense, one of the first statements of a virtuous circle linking productivity growth to investment and the latter to productivity growth. Two connected problems emerge from this: the first is essentially microeconomic and it raises the question of how single economic units, or agents, engender productivity growth while the second concerns the latter's macroeconomic effects on economic activity. The paper attempts to tackle these problems by bringing them together in a model of long term growth.

The first step is to consider technical progress as the mainspring of structural transformation. This implies an understanding of the process of specialization which lies at the heart of division of labour. The first section deals with the nature of technical advance as it is generated by economic units. It will be argued, therefore, that technical progress takes the form of innovation which is endogenous to economic activity. The second section indicates that innovative capabilities are firmly rooted in learning processes: they are, therefore, an ongoing adaptive process which evolves in time and space. The third and fourth sketch out an evolutive model and produce a mathematical formulation. The last section provides a summing up.

## Ways and means

If viewed within the framework of A. Smith's relationship between division of labour and productivity growth, technical change appears as a cumulative process which is endogenous with respect to economic activity. The problem of technical progress, therefore, is a problem of innovation and diffusion. The basic reason for a positive relationship between specialization brought forth by division of labour and productivity resides precisely with the innovations that the former generates and which would have been very difficult to come by in its absence. Microeconomics as well as economic history seem to support this view and allow to cast the assumption in analytical form.

Technical progress is not determined entirely by endogenous forces, however. The impact of science is, especially in modern times, of great relevance in determining technical change. The roots of scientific achievement lie with factors which are not explained by the process of economic activity. While not within the scope of this paper, explanations are to be sought in broad shifts of methodological paradigms, in turn the outcome of changes in the worldview and fundamental ways of thinking. Scientific effort is also closely related to institutional arrangements, to state policies designed for the purpose and to education. None of these factors can actually be envisaged as endogenous. It is, however, crucial that an economic and technical environment exists to bridge the distance between scientific achievement and applide technology and innovation.

In the case just described entrepreneurs, as Schumpeter pointed out in his seminal contribution[1], are provided with opportunities to be exploited by innovative investment. A cluster of innovations, possibly explained by scientific break-throughs, lie according to this author at the root of a long-term upswing in which early adopters reap high profits, or technological quasi-rents. The latter are then eroded away by the band-wagon effect, by diffusion to the entire industry and eventually the economy. The investment inducement, therefore, gradually, wanes, giving way to a downswing as profits are further squeezed by increasing costs. Whether this is a sufficient explanation of a long wave is still quite debatable, but it provides a sound reason for an initial round of exogenous investment led by technical opportunities.

Superimposed on the exogenous and partly thanks to it, endogenous technical progress occurs to strengthen structural change. The degree of development of an economic structure notwithstanding, at any given time there is an extant system of technically specified economic activities in view of a specific output. Employment of labour follows, of course, rules which are socially and politically established. This system is formed by physical places and means of production, a stock of capital goods, which embody the economy's technical capabilities. In turn, they imply specific knowledge, ability and know-how. Combining the latter with the former activities take place as acts, tasks and skills giving shape to sequences which have been termed «routines»[2]. This combination is what can actually be considered as a given technique at a given point in time;

a technique which implies a well defined, in the above sense, production specialization. In any economy, however, there is not just a single technique in use to obtain a given output: diffusion implies that at any given time there is, in fact, a set of different techniques. It may, however, be assumed that a best practise exists which more or less slowly spreads through the system by adoption and obsolescence. It is on this best practise that discussion is proposed.

The set of techniques in existence, the economy's technology, is the result of past innovative choice. Innovative possibilities, in turn, are defined and constrained by such techniques, by the means of production in which they are embodied and by the routines which are applied. The fact that they do take place gives rise to two very general processes: (*i*) the first is a process of learning concerning how to produce a specific output, this is what is generally called learning-by-doing; (*ii*) the second is also a learning process but it focuses on the use of means of production and thus on ways to improve them: this is generally known as learning-by-using. These processes have a chance of occurring which is greater the greater is the achieved degree of specialization of the given technique on which «routines» operate. Thus, the more autonomous and specialized have the various stages of integrated production become the greater is the intensity of learning processes.

The given technique and organization set the domain of possibilities, which is susceptible of being enhanced, and also the constraints, which are susceptible of being lifted, of a system of production: something which is understood and learnt in time. This concept has a very relevant consequence for technical progress and change: improvements are the solution of a search which is determined by extant conditions. They are, in fact, the result of *localized search*[3]. The set of elements, mentioned above, defining the extant technology, the functioning of capital goods, the available skills continuously pose problems derived from their specific features and which bound likely solutions. From this perspective the innovative process may be thought of as a steady process of solution-seeking concerning problems defined by a given technical framework.

A search accomplishing results, i.e. solutions given to technology determined problems, leads to a new technological set-up no matter how small the innovation is. This point needs stressing: the innovative process does not deal just with outstanding technical change or break-throughs; it concerns, rather, small incremental innovations. It is their repeated occurrence, however, which generates a process whose characteristic is that of being sustainable in time: any new achievement is the starting point for the next searching effort because of the new problems arising from the innovation, from the newly acquired capabilities, from enhanced skills.

## The learning process

Economic theory has recently taken in serious consideration what actual experience has always shown: i.e. that economic activity engenders learning processes. The latter are crucial for economic development and yet they are better understood in today's fully industrialized large scale economies and from their historical genesis. In this context, for example, Lundberg had observed that in spite of lack of investment for almost 15 years since the start of operations, implying that equipment had remained the same, the Horndal steel mills in Sweden had experienced a labour productivity growth of two per cent per annum. Paul David has analyzed a similar phenomenon in the cotton spinning activity of the Lawrence no. 2 mill in Lowell, Mass. between 1834 and the American civil war. Another often quoted example showing the pervasiveness of learning processes is T.P. Wright's study on the airframe industry. He has shown that productivity rose according to a very discernible pattern: the number of working hours per airframe required fell according to the function $N^{-1/3}$, where N is the total number of airframes previously produced. Generations of economists are now well acquainted with K. Arrow's famous 1962 article. He assumes that learning processes take place mainly but not exclusively in capital goods industries. New plants carry improvements from which users benefit through increased productivity. Labour productivity thus rises with each successively installed piece of capital equipment. If G is its serial number then the following expression holds:

$$\lambda(G) = bG^{-n}$$

where $\lambda(G)$ is the quantity of labour required to man equipment of serial number G.

The assumption of learning taking place in sectors producing capital goods is, of course, quite restrictive: it does, in fact, happen elsewhere. Yet, this assumption highlights the strategic role that these sectors play as producers of innovations. The reason is quite simple: in practice, any change in production procedures requires some innovation in capital goods. Producers of such goods are continuously challenged to put out more performing equipment to meet users' demands and needs. Capital producing sectors are, therefore, the locus of embodied technical change. Historically they have evolved through successive specialization. In as yet underdeveloped economies, producing implements and rather basic equipment is still an undifferentiated part of a basic production process; say, that of necessities. Nuclei of rudimentary specialization have, however, arisen quite early in history; small craftsmen's workshops to process metals, wood, and to produce tools have actually made up the first centers of specialized instrument making. Where stimuli to increase output materialized the necessity to devote greater attention and time to specific problems led to greater specialization and autonomy; this in turn fostered improvements and innovation. The capital goods sector, therefore, evolves because of its innovative activity and the degree of specialization reached is a stimulus for its intensification.

This property is, of course, quite visible in a generalized exchange environment. In this case, the sale of the sector's current output depends on its effective demand, that is on the whole economy's gross investment. In the long run, short-term cyclical variations notwithstanding, the latter depends on expected rates of return. Their magnitude, in turn, depends on production methods which are likely to be used, for any given wage rate. The capital goods sector is, in this case, continuously stimulated to provide cost reducing solutions to production problems since this is the road to attract demand for its own output.

The sector in question is central also to economies which have not yet fully developed capitalist modes of production. In this case, however, the dynamics of its evolution will be quite different, generally lower. The activity of a capital goods sector establishes a link between producers and users which is conducive to the second type of learning processes: to learning-by-using. Research in the field of industrial economics has strongly emphasized this relationship[4].

The fundamental characteristics of the innovative process centered on learning are those of being continuous and cumulative. Each innovation leads to a new technical and organizational environment which is the base for further innovations. The process gives rise, in time, to a trajectory[5].

As it has been seen, a trajectory implies evolution towards greater autonomy and specialization. More specifically the process creates means of production which are at first tied to a specific final good or to a basket of goods but which later find application in other branches of industry. Economic history has again frequently given evidence of this evolution. Paul David, for instance, has discussed the development of a textile machine industry in New England[6]: at first machines were manufactured by specialized craftsmen and machinists within the premises or in small shops around cotton mills. Once sufficient experience and know-how had been gathered and thanks to prosperous market conditions full fledged firms and plants were then established: in time, a sophisticated textile machinery industry arose which, in turn, stimulated further specialization on account of its own demand for tools, materials and intermediate inputs.

The process can be observed almost everywhere. Recently, the Italian experience with the so called industrial districts has come under the spotlight[7]. The food processing machine industry mushrooming around Parma is a good case in point: some of the firms which today produce numerically controlled steam generators or electronically operated food sterilisers started off as cauldron makers in shops attached to farms. Shifting geografically to the northernmost side of Europe in Finland a somewhat similar story can be told for the wood industry spinning off its own machine tool sector and then hardware and software linked with it.

But learning processes and localized search taking place in the capital goods sector do not yield results at random. Their direction is oriented by bottlenecks created by earlier innovations, by shortages of intermediate inputs, by labour costs, i.e. by what N. Rosenberg calls focusing devices.

## An evolutionary Model

Modern evolutionary theory is quite relevant for economic development. It must, however, be extended to take into account exogenous events which are not necessarily explained by evolution, at least not economic evolution. In the previous section it has been pointed out that science and state intervention may provide powerful incentives for technological development and eventually innovation. But given the foregoing considerations it is quite apparent that innovative change occurs along trajectories: technical progress, as described above, is not the sum of random events but it is determined by intelligible and sometimes foreseeable factors. It actually unfolds as a sequence of specialization causing both complementarity and externality effects. In this context, the producer-user link is of crucial importance; the reason lies in the fact that it is thanks to this linkage that results due to innovative processes can actually be implemented and finally set to work, and it is because of this relationship that a strong economic interest arises for both. To producers, innovating users' processes is an economic must which is stronger the stronger is competition. As it has been mentioned, users gain because of the cost reducing opportunities associated with innovations actually embodied into equipment by producers. The link between them is what makes them visible. Schumpeter's idea of an investing entrepreneur who exploits the opportunities of a basically exogenous technical progress can be quite strengthened since, because of the link between capital goods producers and users, the latter becomes to a considerable extent endogenous.

The rise and growth of an autonomous and specialized capital goods industry can actually play the role which has been indicated only if the linkage turns out to be efficient. Efficiency is, in turn, insured if there is an element of urgency in producing innovations. This is provided by a market mechanism and thus by the economic struggle to protect one's own market share or to gain a larger one. Institutions can also provide stimuli to innovate through appropriate incentives. In actual experience, it is the combination of the former with the latter which is the rule. The failure of planned Eastern European economies, apparently well endowed with capital goods sectors, to run them efficiently is due to the lack of both.

Thanks to this element of necessity a virtuous circle is established between producers and users: by innovating, the former cut costs and increase profits in users' production processes, by increasing demand, the latter strengthen producers' capacity for output as well as for innovation.

## A formal analysis

There is no canonical form to model technical progress. Taking a rather general point of view, it may be assumed that positive variations of the rate of return, in the long run, are the consequence of innovations, in the broad sense which is here adopted. The problem, however, lies with making tecnical change the result of innovative efforts. The latter's nature is typically microeconomic: firms are, in fact, the real protagonists even if rudimentary and quite unsophisticated. An aggregate viewpoint shall, in spite of this, be maintained but the distinction between capital and consumer goods producers will also be adopted.

In previous paragraphs it has been argued that innovative sequences enlarge capital producing sectors since production processes become more roundabout. This follows, in fact, from the progress made by the division of labour and a considerable body of evidence has been given to support it[8]. It may therefore be assumed that technical progress has manifested itself as an increase in capital labour ratios; surely, not a very rigorous measure since the relative prices which must be used as weights are invariant with neither income distribution nor with technical conditions of production. Being evidence of its positive association with labour productivity quite strong, it may nevertheless be taken as an empirical measure. Let then:

1. $$Z_c \equiv (K/L)_c \; ; \; Z_k \equiv (K/L)_k$$

be the capital-labour ratios in the consumer and capital goods sectors respectively; the former an users' industry, the latter both an users' as well as a producers' industry. In a very stylized fashion, the dynamics of the innovative process can be rendered by the following equation

1.1. $$\dot{Z}_c = Z_i(I_k^n, S_i) \qquad i=c,k$$

The first independent variable can be termed the innovative investment which producers as a whole undertake to carry out localized search. $I_k^n$ obviously acquires a different significance according to the mode of production and degree of development. In quite a sophisticated entrepreneurial environment it may take the form of Research and Development expenditure; in a less formalized environment it is expenditure which includes such items as non commercial prototypes, information search, technical updating etc. It may safely be assumed that village blacksmiths in Sahelian Niger devote a negligeable share of their investment expenditure, which is very modest, to innovative investment. Indian machine tool industries, on the other hand, certainly spend a non trivial magnitude to gather innovative information or to adapt imported technologies. South Korean or Taiwanese electronic industries may however perform, although not necessarily at a very high level, their own research and development.

The determinants of innovative investment, in the broad sense which is here used, are quite complex. In view of the previous discusison on localized search, it can be argued that spurring or focusing devices of such search, which requires financial outlays, derive from the properties and the problems inherent in existing techniques. It is from the problems they raise as well as from the opportunities they offer in terms of further development or, and this is quite important, of further application to related, either backward or forward linked, sectors that a quest for innovative solutions is made. In this simple, two sector model, this feature of evolutionary progress can be rendered by assuming innovative expenditure, carried out by the capital goods producing sector, as a function of the achieved level of technology which is here proxied by the capital-labour ratios $Z_c$, $Z_k$. The latter, however, cannot alone be the sole determining factors for any financial effort, especially if not directly made to increase income generating capacity in the short term, requires means to sustain it which are in turn explained by market success. In the case of capital goods producers market succes can be measured by the strength of demand specific to the sector, i.e. by the current volume of investment. A strong demand warrants past search efforts and innovations, it fulfills expectations placed on previous outlays. The following function can, therefore, be conjectured:

2. $$I_k^n = I_k^n\ (Z_k, Z_c, I)$$

The variables which have been indicated with S represent effects on labour productivity due to learning processes: by doing as well as by using. Such processes are not, generally, instantaneous: for any given level of cumulated output, in the first case, and for any size of the capital stock, in the second, they require time to come to completion. In consequence, variations in variables S measured in terms, say, of labour productivity per unit of time, are a function of the level of investment, which in equilibrium is the current output of the capital goods sectors but which is also the explanatory variable of current consumption via the multiplier, and of the attained level of S:

3. $$\dot{S}_i = S_i(I, S_i) \qquad i=c,k$$

Equations 1 and 3 express in a highly stylized form microeconomic behaviour of an adaptive kind. Yet they both depend, either directly or indirectly, from a macroeconomic variable, i.e. from the current flow of gross investment. The macroeconomic aspect, i.e. the determination of effective demand, is the missing link to generate the system dynamics. By adopting a very straight forward keynesian viewpoint, take economic activity to depend, via the multiplier, on investment decisions. These, in turn depend in the long run on profit expectations. It is on the latter that technical progress has a decisive impact. Thus, the Schumpeterian conjecture that technical progress supplies a domain of opportunities which entrepreneurs exploit by investment holds. There is, however, no *a priori* reasons to rule out the hypothesis that an enlightened planner may also act likewise through an incentive system.

## The investment equations

To Schumpeter past inventions together with pioneering forms of innovation provide, where entrepeneurial attitudes are strong enough, stimuli to initiate a long wave upswing. This occurs when a cluster of innovations as yet scarsely adopted but already sporadically tried set off high investment demand because of the profit opportunities provided thereby. The innovators who develop commercially viable new goods either of a consumption or of a capital kind stand to reap profits quite above the norm. The latter may be defined by the profit rate applying equally to all firms when the innovation has been thoroughly adopted by the industry. Adopting the long term view which is characteristic of this paper, such rate of profit is the one common to all industries, following from a given wage rate and from the underlying best practise technology. Above normal profits, however, are gradually eroded away as more adopters come to the fore, prices are lowered as a consequence of weaker oligopoly.

At the outset of the temporal process beginning with new and radical innovations the market, possibly in a downswing trough, may be assumed as divided up in consolidated oligopoly shares. Breaking away from stagnation and acquisition of larger market leverage are the prime movers of initial investment. Thus, entrepreneurs exploit in this sense opportunities provided by exogenous technical progress. It may also be assumed, however, that incentives are provided by long-sighted economic policies aiming at enhancing economic activity. As investment gains momentum on account of followers and imitators and thus as innovations spread through the industry, the so called band-wagon effect, the profit rate gradually falls towards the norm: it is therefore a decreasing function of the share of the innovative capital stock installed in each industry. This leads to define a first investment function; as long as there is a positive difference between the attainable rate of profit and that set by the above defined norm investment occurs. The kind of investment which is so determined is, in a Schumpeterian sense, creatively destructive: it sets up capacity for new goods which substitute old ones, be they consumer's of producer's. In so doing old capacity becomes either inactive or obsolete as investing firms drive laggards out of the market. Aggregate demand is, prior to the innovating investment, stagnating or even falling; new capacity displaces the old, it does not necessarily add to it. But as activity levels increase on account of multiplier effects an upswing may be started.

From the first critical innovations, tecnological trajectories are then developed thanks to localized search and learning. Attainable profit rates, assuming wages constant, increase on account of innovations which are derived starting from technical break-throughs. This can be achieved through replacement of old with new capacity. In fact existing capital stock can be scrapped faster thanks to technical obsolescence. Thus, while leaders' quasi rents are gnawed away because of diffusion normal rates increase on account of continuing technical progress. Let the difference between the two rates be:

4. $$x_i = r(s_i) - r(Z_i) \ ; \qquad i = c,k$$

where $s_i = (K_{ni}/K_{oi})$ and $K_{ui}$ and $K_{oi}$ respectively the new innovated capital stock and the old, inherited from the past. By definition $k_{ni} = \int_{t_0}^{t} I_i d\tau$ with $t_0$ being the date when innovations were introduced. Furthermore:

$$\text{for} \quad s_i \leq s_i^* \ r'(s_i) \geq 0 \ \text{and}$$
$$\text{for} \quad s_i > s_i^* \ r'(s_i) < 0$$
$$r'(Z_i) > 0 \ ;$$

The difference between normally attainable rates on the bassi of the new technology and above normal ones earned by early adopters defines an investment motive which can be generally rendered by the following function:

5.1. $$I_i^x = I_i^x(x_i) \qquad s.t. \ I_i^x(0) = 0 \ ; \qquad \frac{dI_i^x}{dx_i} \geq 0 \ ; \left.\frac{dI_i^x}{dx_i}\right|_{x_i=0} = 0$$

Induced innovations developed along a trajectory provide a second and independent investment motive. The impact of such innovations is that of making existing capacity obsolete. The faster is the pace of endogenous technical progress in the sense illustrated in previous paragraphs the more impelling it becomes to substitute old plant for new to take advantage of higher rates of return. Thus, each sector is likely to scrap and replace for newer equipment the faster is the advancement of technical progress as measured by the capital labour ratio[9]. Yet, the rate of substitution is hindered by the vintage structure of capital goods. The newer are the latter the more expensive it is to invest for more advanced plant.

The following equation can, then, be envisaged:

5.2. $$I_i^r = I_i^r(Z_i, K_{ni}) \;;\; \frac{\partial I_i^r}{\partial Z_i} > 0 \;;\; \frac{\partial I_i^r}{\partial K_{ni}} < 0 \;;$$

While investment is taking place to take advantage of innovations, firms necessarily formulate a target new capital stock which they deem, on account of both technical and organizational considerations, as appropriate to demand. This gives rise to an adjustment process. Consider the simplest multiplier formulation:

5.3. $$C = \bar{c}_0 I \;;\; \bar{c}_0 = \bar{c}/1-\bar{c}$$

As it is the norm in capital-adjustment models, let the desidered new capital stock be defined as $K_{ni}^* = v_i \bar{c}_i I$, where $\bar{c}_c = \bar{c}_0$ and $\bar{c}_k = 1$, and where $v_i$ is the proportion of new capital to demand in both sectors. The latter can be assumed to be, for simplicity's sake, constant. The adjustment equation can be written as:

5.4. $$I_i^a = I_i^a(v_i \bar{c}_i I - K_{ni}) \qquad i=c,k$$

Summing up over the three investment equations and the two sectors, the general investment equation can be expressed as:

6. $$I = I^x(x_c, x_k) + I^r(Z_c, Z_k, K_n) + I^a(I, K_n)$$

By substituting 2. into 1.1 and by differentiating 6. the following system of non-linear differential equations is obtained

7.
$$\begin{aligned}
\dot{Z}_c &= Z_c(Z_c, Z_k, S_c, I) \\
\dot{Z}_k &= Z_k(Z_c, Z_k, S_k, I) \\
\dot{S}_c &= S_c(Z_c, S_c, I) \\
\dot{S}_k &= S_k(Z_k, S_k, I) \\
\dot{I} &= \frac{I_x^x r_{z_c} + I_{z_c}^r}{1 - I_I^a}\dot{Z}_c + \frac{I_x^x r_{z_k} + I_{z_k}^r}{1 - I_I^a}\dot{Z}_k + \frac{I_x^x r_s + (I_{kn}^r + I_{kn}^a)}{1 - I_I^a} I
\end{aligned}$$

Note that the last equation has been simplified by setting

$$\frac{d(K_{nt}/K_i)}{dt} = I_i \quad \text{and} \quad I_{x_c}^x r_{s_c} I_c + I_{x_k}^x r_{s_k} I_k = I_x^x r_s I$$

The system expresses, if a solution exists, a movement in which technical change is partly endogenous since it depends on acquired technology as well as on investment. It is the latter to be influenced by exogenous events, assumed to take the form of innovation clusters, through the $r(s_i)$ function as opposed to $r(Z_i)$. Radical innovations are likely to set off investment attracted by high rates of return, at least for those leading the band-wagon. In this sense the system is quite sensitive to initial conditions, especially on investment.

System 7. is likely to be quite complex as to its analytical form. Local stability conditons may, however, shed some light on its behaviour. Let 7. be considered where $\dot{S}_c$, $\dot{S}_k$, $\dot{I}$, $\dot{Z}_c$, $\dot{Z}_k$ are all zero. The Jacobian is:

8. $$J = \begin{vmatrix} Z_{cc} & Z_{ck} & Z_{cs} & 0 & Z_{cl} \\ Z_{kc} & Z_{kk} & 0 & Z_{ks} & Z_{kl} \\ S_{cc} & 0 & S_{cs} & 0 & S_{cl} \\ 0 & S_{kk} & 0 & S_{ks} & S_{kl} \\ I_{zc} & I_{zk} & I_{sc} & I_{sk} & I_{l} \end{vmatrix}$$

whose elements are the partial derivates at that point.

The last row of 8. is obtained by setting the coefficients of the last equation equal to $\alpha_1$, $\alpha_2$, $\alpha_3$ respectively and then by substituting for $\dot{Z}_c$ and $\dot{Z}_k$. The following are then obtained

8.1. $$I_{zc} = \alpha_1 Z_{cc} + \alpha_2 Z_{kc} \; ; \; I_{zk} = \alpha_1 Z_{ck} + \alpha_2 Z_{kk} \; ; \qquad I_{sc} = \alpha_1 Z_{cs}$$
$$I_{sk} = \alpha_2 Z_{ks} \; ; \qquad I_l = \alpha_1 Z_{cl} + \alpha_2 Z_{kl} + \alpha_3 \; ;$$

A necessary but not sufficient condition for the linearized system to yield negative real part roots, i.e. to be able to converge[10], is that the trace of 8. be negative, that is:

9. $$tr(J) = Z_{cc} + Z_{kk} + S_{cs} + S_{ks} + I_l < 0$$

A set of sufficient conditions is satisfied if all elements on the main diagonal are negative and each is in absolute value greater than the sum of the absolute value of remaining elements on either the same row or column. It is quite clear that the roots of 7. depend on the analytical form of its functions. In order to verify whether either or both conditions can be verified conjuctures have to be made on the learning functions, innovative expenditure and endogenous technical progress.

As mentioned in previous paragraphs, learning of both types is not instantaneous. This means that although cumulated output in the case of learning-by-doing and the capital stock in the case of learning-by-using both foster increases in the levels of skills and expertise their acquisition is gradual and bounded. For any given level of current output, which is tantamount to assuming a constant increase in cumulated output, and for a likewise given level of investment, implying a constant addition to stock, the increase in learning depends primarily on the acquired level of skill. The higher is the latter, the greater is its increase. In both cases, the thrust of experience remains unchanged with replication of production levels and constant growth of the capital stock; yet cumulated learning due to past exposure to both production and using problems warrant further learning; the latter being greater the greater is the former. This holds, however, up to a point. Each time new equipment is installed, a new and improved technique is implemented. Productivity is likely to rise but only as the people who man it learn. How far the learning process can go is defined by the new technique potential, a matter of technological forecasting. Thus, productivity can only be raised up to a level which establishes the technique final performance. It is the latter, therefore, to bound the learning process. But as the latter approaches this limit decreasing returns to learning efforts set in. Improving skills becomes increasingly difficult which means that the limit acts as an asymptote. Early headstarts in manning the new technique and equipment are followed by tapering improvements. At the outset newly acquired skills and know-how spur further learning at an increasing rate but as the limit is neared improving personal skills becomes more difficult.

For given output and investment, therefore, learning gradually rises according to a logistic curve toward its forecast maximum. Let the latter be called $\bar{S}_i$; i=c,k. $\bar{S}_i$ is, according to the foregoing discussion, the maximum attainable productivity level given the new technique introduced by new capital equipment. As technical progress unfolds bringing about obsolescence and replacement, thus as new equipment is substituted for the old, $\bar{S}_i$ is likely to increase. This makes it a function of $Z_i$, the capital-labour ratio which is used in this context as a proxy for levels of technical progress. Let, then, $\bar{S}_i$ be written as:

10.1. $$\bar{S}_i = \bar{S}_i(Z_i) \ ; \ i=c,k \ ; \ \bar{S}_i' > 0 \ ; \ \bar{S}_i(0) > 0 \ ;$$

A logistic curve is held here to satisfactorily describe the learning process taking place within the confines of a given technique. Although originally used to formalize the spread of epidemies in a population of given size and then to account for diffusion of techniques among firms in a given market (Mansfield 1968), it can usefully be applied in the case at hand. A logistic curve does, in part, analytically describe the generation, or the gradual acquisition of skills asymptotically to saturation as expressed by $\bar{S}_i$.

Let the two equations, in both sectors, be

10.2. $$\dot{S}_c = (c_o I)^{\alpha} \left[\bar{S}_c(Z_c) - S_c\right] S_c \ ;$$

10.3. $$\dot{S}_k = I^{\beta} \left[\bar{S}_k(Z_k) - S_k\right]$$

The solution of which for given levels of I and $Z_i$ is

11. $$S_i(t) = \frac{\bar{S}_i(Z_i)}{\left[\bar{S}_i(Z_i)S_{oi}^{-1} - 1\right] e^{-a_i \bar{S}_i(Z_i)t} + 1}$$

where $a_c = (\bar{c}_0 I)^{\alpha}$, $a_k = I^{\beta}$ and $S_{0i}$ is the initial level of skills measured by productivity per head in either sector. It is the arbitrarily given initial condition of $S_i(t)$ assuming all other variables as constant. As it can be easily verified

$$\frac{\partial S_i}{\partial Z_i} > 0 \ ; \ \frac{\partial S_i}{\partial a_i} > 0 \ ;$$

$S_i(t)$ shifts upwards with both investment and technical progress. In fact, a new curve would have to be traced for each new level of either I or $Z_i$ or both. Each new such curve inherits, as the initial value, the last $S_i(t)$ attained by the previous one. This assumption of an initial condition equal to the previously achieved level of skills is quite strong, of course. It may be argued that when entirely new, or highly innovative equipment is installed, labour productivity may initially fall reflecting workers' lack of experience. On the other hand, technological advancement may bring about productivity increases from the outset.

It is quite clear from equations 1.1 and 6. that technical progress explains a good deal of the system dynamics. According to the discussion set forth in previous paragraphs, the variables which explain technical change along a trajectory are the level of acquired learning as shown through labour productivity and innovative expenditure. The two interact in localized search for problem solutions. In a very general sense, it is to be expected that developments initiated by a change in a technological paradigm be much faster after the initial stages to slow down as technologies are perfected and ameliorated. In some cases it is quite possible to forsee a limit to the process. This behaviour can be rendered by a simple function:

$$\dot{Z}_i = \bar{Z}_i \left(1 - e^{-S_i I_k^n}\right) \qquad ; \ i=c,k$$

12.

$$\frac{\partial \dot{Z}_i}{\partial S_i} > 0 \ ; \qquad \frac{\partial \dot{Z}_i}{\partial I_k^n} > 0 \ ; \quad \frac{\partial^2 \dot{Z}_i}{\partial S_i^2} < 0 \ ; \quad \frac{\partial^2 \dot{Z}_i}{\partial I_k^{n2}} < 0 \ ;$$

The interaction between $S_i$ and $I_k^n$ takes a multiplicative form; each amplifies the impact of the other. Negative second derivatives express the idea that decreasing return to innovative input prevail; a statement which seems to be corroborated by evidence.

As to the shape of investment inteded to develop innovations, i.e. of the $I_k^n$ function, it was found to depend on the state and complexity of technology and on the ability to finance costly outlays. Literature on research and development has often expressed such expenditure as a proportion of gross turn-over and, at a macroeconomic level, as a function of gross domestic output. The existence of a threshold below which no R.&D. efforts are carried out has also been empirically verified. Above, the proportion may be thought to increase with the «challenge» that the existing technological set-up poses as measured by $Z_k$ and $Z_c$. No great analytical detail is here required: it is sufficient to assume that a fraction of GDP above a given amount $\bar{Y}$ is devoted to innovative outlays as an increasing function of $Z_k$ and $Z_c$.

$$I_k^n = \bar{C}_0 f(Z_c, Z_k)(I - \bar{I}) \; ; f(\cdot) \leq 1$$

13. $$f'_{z_i} > 0 \; ; f''_{z_i} < 0 \quad \text{for} \quad I \geq \bar{I}$$

and

$$I_k^n = 0 \qquad \text{for} \quad I < \bar{I}$$

Note that the shape of f(·) is clearly influenced by the way markets are organized.

The way functions have been specified, there is more than one point in which $(\dot{Z}_i, \dot{Z}_k, \dot{S}_c, \dot{S}_k, \dot{I}) = 0$. Indeed this may occur anywhere for $0 \leq I \leq \bar{I}$ provided $\bar{S}_i(Z_i) = S_i$. For I=0 stationarity is assured at any level attained by the new capital stock. For $I \leq \bar{I}$ no active search takes place and, thus, no technical change occurs in spite of continuing learning. For I=0 to occur in this phase, however, $\alpha_3=0$ is required. Since $(I^r_{kn} + I^a_{kn}) < 0$, this happens only if $r_s > 0$ an event implying a new capital stock share which still affords rising returns. In this case if investment is not strong enough to rise above $\bar{I}$, stagnation may happen. $\alpha_3 = 0$ is quite unlikely to occur, though; for capital stocks above, and even more so for ones exceeding $s_i^*$, $\alpha_3 \gtrless 0$ in relation to $1 - I^a_I$, $I^a_I$ is simply an accelerator reflecting the speed of adjustment to rising demand. If fast enough $1 - I^a_i<0$ and $\alpha_3>0$. In this case, even if $(\dot{Z}_i = 0, \dot{S}_i = 0)$, $\dot{I} > 0$ and thus I will soon exceed. $\bar{I}$. While this implies positive rates of $\dot{Z}_i$, rising new stock and excess capacity may bring investment to zero. If $1 - I^a_I > 0$, i.e. for a weak accelerator, $\alpha_3$ is negative and if $(\dot{Z}_i, \dot{S}_i) = 0$ contraction occurs. A falling stock, however, may reproduce a situation in which investment is again very profitable, i.e. $r_s > 0$ and eventually $\alpha_3 > 0$.

While stationary points are multiple, the Jacobian signs provide a clue to eventual stability. As for the necessary condition, note that on account of 13., 12. and 10.2-3, it is:

$$Z_{ii} = \partial \dot{Z}_i \Big/ \partial I_k^n \cdot \bar{c}_0 (I - \bar{I})\, f'_{zi} \geq 0 \qquad \text{if} \quad I \geq \bar{I}$$

hence where stationarity occurs $Z_{ii} \leq 0$;

$$S_{is} \gtreqless 0 \qquad \text{if} \quad \frac{1}{2}\, \bar{S}_i(Z_i) \gtreqless S_i$$

Since $\bar{S}_i(Z_i) = S_i$ where $\dot{S}_i = 0$, $S_{is} < 0$.

As to the sign of $I_I$, it depends crucially on the accelerator $I_I^a$ and the stationary point. Let it be assumed that $I < \bar{I}$ implying $\alpha_3 = 0$. Since $Z_{iI} = 0$, $I_I = 0$. The necessary condition for convergence is satisfied. If, however, $I = \bar{I}$ and $1 - I_I^a < 0$, a case of strong reaction to the demand pull, then $Z_{iI} > 0$ as well as $\alpha_1$ and $\alpha_2$, thus $I_I > 0$. In this case, provided $I_I$ is large enough and or $Z_{ii}$, $S_{is}$ small enough in absolute value, convergence may not occur. The economy finds itself in such a situation when the share of the new capital stock is still sufficiently small and increasing returns are to be obtained from the new technologies while at the same time replacement and new capacity addition can both be discouraged by the new vintages and by excess supply. A demand increase, however, may be sufficient to set the economy in motion again.

Let be assumed, instead, that $1 - I_I^a > 0$, i.e. the accelerator is weak. $\alpha_1$ and $\alpha_2$ are now negative and, thus, the necessary condition for convergence is met. A weak reaction to demand stimuli may, therefore, keep the economy stagnating. If stationarity occurs for $I = 0$ and $1 - I_I^a > 0$ then, $\alpha_3 < 0$ and again the necessary condition is satisfied. There is a possibility that $\alpha_3 > 0$. This occurs for $r_s > 0$ and a small share of new to old capital stock; in this case, however, it is quite unlikely that I = 0. For $1 - I_I^a < 0$ the opposite is true.

Sufficiency conditions are, of course, more difficult to ascertain. A set of sufficient conditions is satisfied when, being the elements of the main diagonal all negative, they are in absolute value greater than the sum of the absolute values of elements lying on the same row or column. On account of the values taken by partial derivatives in $\dot{J}$ at stationary points, the following conditions must be met:

14.
$$|Z_{cc}| > |Z_{ck}| \; ; \; |Z_{kk}| > |Z_{kc}| \; ; \; |S_{cs}| > |S_{cc}| \; ; \; |S_{ks}| > |S_{kk}|$$
$$|I_I| > |I_{zk}| + |I_{zc}|$$

The meaning of these conditions is, in a sense, quite simple. They state that the impact of a variable on its own rate of change be, in absolute value, greater than that of other variables. Thus, the impact of investment, directly or indirectly through the feed back on technical progress, be greater than that which the latter exercises on account of acquired levels $Z_k$ and $Z_c$ in both sectors. The same applies to learning: it is required that in each sector it explain its own changes more than the level of achieved technical progress, etc. Although no theory can a-priori be deviced to insure that 14. are met, it is empirically plausible that they are, provided the necessary condition is, in fact, satisfied. The following table sums up these results.

| | $I = 0$ | | $0 < I < \bar{I}$ | $I = \bar{I}$ | |
|---|---|---|---|---|---|
| | $1-I_I^a<0$ | $1-I_I^a>0$ | | $1-I_I^a<0$ | $1-I_I^a>0$ |
| NEC. | $Z_{ii} < 0$<br>$S_{i\varepsilon} < 0$<br>$I_I > 0$<br>$tr(j) \gtreqless 0$ | $Z_{ii} < 0$<br>$S_{i\varepsilon} < 0$<br>$I_I < 0$<br>$tr(j) < 0$ | $Z_{ii} < 0$<br>$S_{i\varepsilon} < 0$<br>$I_I = 0$<br>$tr(j) < 0$ | $Z_{ii} < 0$<br>$S_{i\varepsilon} < 0$<br>$I_I > 0$<br>$tr(j) \gtreqless 0$ | $Z_{ii} < 0$<br>$S_{i\varepsilon} < 0$<br>$I_I < 0$<br>$tr(j) < 0$ |
| SUF. | not satisfied | possibly satisfied | not satisfied | not satisfied | possibly satisfied |
| | — | possible convergence | — | — | possible convergence |

One of the above shown results is worth stressing. Convergence is likely to occur when the accelerator is weak. Thus, because the economy does not react rapidly to demand if it happens to hit a stationary point, it is quite possible that it remains there. Hence, in spite of the endogeneity of technical process and impulses provided to investment, the economy may actually stagnate. This emphazises the role that demand induced investment plays in keeping the economy growing. For stationarity to occur it is necessary, however, that learning progresses slowly to near the saturation point and that no searching occurs.

The question to be asked at this stage of the analysis is whether the accelerator term $I_I^a$ in an economy such as the one being described is greater or smaller than one. As it can be easily seen by looking at 6., a greater than one accelerator implies a predominance of the adjustment mechanism on the other components of investment. In this case technical progress induced addition to stock by bringing about a situation of excess supply causes overall investment to decrease. Viewed in terms of rates of change, the last equation of 7., this is a case in which, in spite of positive reactions to technical change, i.e. of positive numerators $\alpha_1$, $\alpha_2$ and $\alpha_3$, $\dot{I}$ is negative. An economy in which reaction and adjustment to demand are strong stifles the positive impulses of technical change.

Conversely, an economy with a slow accelerator $I_I^a$ engenders positive rates of change on account of $\dot{Z}_c$ and $\dot{Z}_k$ but, then, it is likely to get caught in stagnation if investment does not rise above the threshold required to carry out localized search. As shown by the table this is the case when attraction towards stationarity is quite high.

Further examination of 7. reveals the following: $(I_{kn}^r + I_{kn}^a)$ are negative, hence after $s_i$ is past $s_i^*$ $\alpha_3$ becomes negative. This is because current investment checks its further growth, when technological quasi-rents have been exhausted, because of the growing size of new stock. Although $\alpha_1$ and $\alpha_2$ are positive, in case of strong technology inducement, $\dot{Z}_i$ and $\dot{S}_i$ gradually slow down on account of decreasing first derivatives, as from 10.2-3 and 12. Thus, as investment in new stock progresses, $\dot{I}$ is likely to become negative. With decreasing investment the economy will sooner or later find itself in a region in which stagnation is likely and one in which convergence to stationarity is also likely.

## Conclusions

The paper holds that technical progress and innovation lie at the heart of the development process. Progressive structural transformation occurs when in integrated but technically primitive economies capital goods producing sectors begin to acquire autonomy and thus to specialize.

Following Schumpeter, it may be assumed that radical innovations of an exogenous kind set in motion an endogenous process which takes place through vertical division of labour, learning and search. At any particular time, the existing stock of capital goods, know-how and skills define the technology being used which is itself the result of past innovative decisions. This technology sets both the bounds of what is technically feasible but also of what can be improved: focusing devices are at work to orient localized search. Solutions of problems and success bring about innovations which, on one hand, spread through the economic system on account of complementarities and externality effects and, on the other, establish the new set of conditions from which further progress stems. This sequence defines the main characteristics of the innovative process: seen from this viewpoint applied technical progress once set in motion by an exogenous source, say a cluster of inventions becomes (*i*) endogenous, (*ii*) continuous, (*iii*) cumulative and (*iv*) non-ergotic.

These basic qualities can be formalized.

A model is shown in which microeconomic innovative behaviour determines, together with accelerator effects, the current level of investment. The macroeconomic determination of aggregate demand and acquired levels of skills focused by technological opportunities explain innovative efforts which, in turn, determine innovative investment. A set of non-linear differential equations formalizes the model.

Analysis of local stability conditions reveal that a system as the one described above has a plurality of stationary equilibria. Results are contradictory. Convergence is likely to occur when the accelerator is weak in which case the system gets caught in a low level equilibrium trap with no technological search. An economy in which reaction and adjustment to demand are strong leaves little growth explained by technical change, indeed excess supply may cause investment to contract towards stationary points. An economy with a slow accelerator, however, is one in which investment is likely to grow riding the innovation wave. In this case, however, if stagnation occurs it is likely to be a low level trap. The economy, as innovative investment progresses and innovations gain ground, slows down because endogenous change becomes weaker.

A developing economy requires initial strong demand to set the process of structural transformation in motion. If it manages to experience endogenous technical change, growth is induced thereby but slows down with weakening technical progress. Schumpeter thought that a long wave might be generated in this process. Whether a system, once fully developed, is able to produce repeatedly the initial conditions that set it in motion is quite open to question.

## Notes

[1] Schumpeter (1939).

[2] See Dosi's (1988) review article on this issue.

[3] See Atkinson and Stiglitz (1969).

[4] See, on this point, N. Rosenberg (1976).

[5] This terminology is employed, for instance, by Nelson and Winter (1982).

[6] P. David (1975).

[7] Piore and Sabel's «Second Industrial Divide» is an example of the interest which 'industrial districts' have stirred.

[8] See Kutznets (1972).

[9] See Ricottilli M. (1988).

[10] See Gandolfo (1977).

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