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# THE SYSTEM DYNAMICS OF COLLECTIVE KNOWLEDGE: FROM GRADUALISM AND SALTATIONISM TO PUNCTUATED CHANGE

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# THE SYSTEM DYNAMICS OF COLLECTIVE KNOWLEDGE: FROM GRADUALISM AND SALTATIONISM TO PUNCTUATED CHANGE[1]

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ABSTRACT. The economics of localized technological change provides an original framework to model the dynamics of introduction of new technologies as the result of the interaction between the inducement to change the technology, generated by the mismatch between plans and expectations, and the characteristics of the system. Collective knowledge emerges when knowledge widening leads to knowledge deepening. The interplay between networking costs and knowledge supermodularity can explain both punctuated and gradual change. Smooth, Marshallian dynamics can easily generate major Schumpeterian discontinuities. The divide between the theories of discontinuous and gradual growth can be reconciled when the essence of the Schumpeterian and Marshallian approach is properly combined. Small variations in the parameters can generate either gradual or discontinuous changes. Punctuated technological change is likely to take place when the interplay between positive and negative knowledge externalities leads to the creation of commons of collective knowledge and hence new technological systems. The correct appreciation of the interactions between individual action and the characteristics of the environment makes room for a system dynamics framework able to explain in a single context both Marshallian gradualism and Schumpeterian saltationism.

JEL CODE: O33

KEY WORDS: Gradualism, Saltationism, Punctuation, Localized technological change, Positive and negative knowledge externalities, Collective knowledge, Technological systems.

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## 1. INTRODUCTION

In the economics of localized technological knowledge each firm has a heterogeneous and distinct knowledge base, rooted in its own 'locus' defined by learning procedures that are specific to the techniques in place and the set of fixed tangible and intangible assets (Atkinson and Stiglitz, 1969; David, 1975). When knowledge exhibits high levels of supermodular complementarity and networking costs are low, however, firms have an incentive to implement the convergence of their own knowledge and competence, so as to increase knowledge complementarity. Commons of collective knowledge emerge when the active participation of firms pushes the direction of the internal research and learning activities towards higher levels of complementarity with the aim to build a systemic integration. Collective knowledge is characterized not only by imperfect appropriability and access to intellectual property rights that are either shared or often not specified or specifiable but also by the role of the intentional networking effort, participation and contribution of each agent. Collective knowledge is the result of the valorization of the elements of latent complementarity among the bits of knowledge possessed by each localized agent (Antonelli, 2001)

Knowledge networking activities help identifying and accessing the sources of external knowledge. On these bases the firm will select and focus the direction of internal learning and research activities in order to integrate them with the characteristics of the external knowledge available. By means of knowledge networking firms direct their research and learning efforts towards the emerging commons of collective knowledge. The emergence of technological systems is the ultimate result of such an effort of exploration, creation and exploitation of knowledge complementarities (Antonelli, 2001).

The analysis of the dynamics of collective knowledge within the framework of the economics of localized technological change can help to provide a synthesis of the divide between Schumpeterian saltationism and Marshallian gradualism.

Smooth, Marshallian dynamics can easily generate major Schumpeterian discontinuities. The divide between the theories of punctuated and gradual growth can be reconciled when the essence of the Schumpeterian and Marshallian approach is properly combined. The economics of localized technological change provides an original framework to model the dynamics of introduction of new technologies. In this approach, the introduction of technological innovations is the result of the interaction between the inducement to change the technology, generated by the mismatch between plans and related irreversible commitments and expectations, and the interplay between positive and negative externalities provided respectively by technological spillover and networking costs.

The correct appreciation of the interactions between individual action and population dynamics makes room for a system dynamics framework able to explain in a single context both Marshallian gradualism and Schumpeterian discontinuities. Within the context of a punctuated approach, in fact, Marshallian gradualism and Schumperian saltationism can be considered as two extreme possibilities between which a continuum of solutions can be identified. Small variations in the parameters of the positive and negative externalities and in the feedback affecting the extent of the mismatch and hence the levels of the inducement can generate either gradual or discontinuous changes.

The rest of the paper is organized as follows. Section 2 presents a brief exposition of two contrasting views about continuity in economic and technological change. Section 3 introduces the notion of localized technological change, stresses the analysis of positive and negative externalities, articulates the analysis of the dynamics engendered by the feedback between localized technological change and mismatch. This section provides also some anecdotal evidence about the relevance of such dynamics in the understanding of the long-term growth in the case of Piedmont, a region of Italy. The conclusions summarize the main results of the work and put them in a broader perspective.

## 2. SMOOTH vs. DISCONTINUOUS CHANGE

The divide between Marshallian gradualism and Schumpeterian abruptness about the rate and direction of economic evolution at large has strong implications for the economics of innovation and new technologies.

According to Alfred Marshall ‘Natura non facit saltum’: “economic evolution is gradual. Its progress is sometimes arrested or reversed by political catastrophes; but its forward movements are never sudden; for even in the Western world and in Japan it is based on habit, partly conscious, partly unconscious. As though an inventor, or an organizer, or a financier of genius may seem to have modified the economic structure of people almost at a stroke; yet that part of his influence, which has not been merely superficial or transitory, is founded on inquiry that have done little more than bring to a head a broad constructive movement which had long been in preparation” (Marshall, 1920, p.xiii).

Joseph Schumpeter provides instead the key reference for a very different view: “We must recognize that evolution is lopsided, discontinuous, disharmonious by nature – that the disharmony is inherent in the very modus operandi of the factors of progress. Surely this is not out of keeping with observation: the history of capitalism is studded with violent bursts and catastrophes which do not accord well with the alternative hypothesis we henceforth discard, and the reader may well find that we have taken unnecessary trouble to come to the conclusion that evolution is in disturbance of existing structures and more like a serious of explosion than a gentle, though incessant, transformation" (Schumpeter, 1939, p.102)[2]. The Schumpeterian approach has always stressed the sudden emergence of new technological paradigms and major technological breakthroughs developing a saltationist interpretation of long term economic growth and technological change. In the Schumpeterian approach discontinuities in long term growth are viewed as a consequence of discontinuities in the rates of introduction of radical technological innovations.

The views about technological change are at the core of the debate about continuity in economic change. Both schools of thought recognize that technological change plays a major role in their respective interpretations.

The gradualist approach emphasizes the role of minor innovations. Technological change takes place by means of a variety of small, incremental steps, characterized by substantial complementarity and cumulability. In the long term the sequence of incremental innovations builds up a major change. No discontinuity however can be found in the continual process of introduction of new technologies and their selection by means of imitation, adoption and diffusion.

The gradualist approach does not necessarily leads to linear change but it is consistent with the traditional neoclassical views about technological change as manna, descending from exogenous scientific progress, or, in a more dynamic approach, as the result of systematic and ubiquitous learning (Arrow, 1962a and b). The gradualist approach is also consistent with the new growth theory. In this approach technological change is the result of the profit-maximizing conduct of firms. They are, in fact, assumed to be able to appropriate substantial portions of the economic benefits stemming from their innovations augmented by the homogeneous access of firms to externalities spilling from the research and development activities conducted by each other firm (Romer, 1986 and 1990).

Gould and Eldridge (1977) have elaborated in biology the notion of punctuated change. In biological punctuation the critical event is exaptation, a special form of speciation, which consists in the application of existing genetic codes to a different ecological context. Separation of the new context is crucial in determining the evolution of the new agents and the eventual, possible emergence of new species. Such separation may occur by means of geographic remoteness, allopatric speciation or exploitation of the periphery of a existing niches. In exaptation, the initial event may consist of a minor change. The interaction with the new environment and the sequential accumulation of small, additional changes however reinforce each other in a new genetic drift which may eventually lead to the emergence of a new species. Occasionally the new specie fits better not only in the new environment but also even in the original one. Punctuation is clearly the result of a gradualist process where

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[2] See Rosser (1991, p.138-140).

incremental changes and feedbacks of the local environment interact and reinforce each other (Gould, 2002).

Joel Mokyr has successfully applied to the economic analysis of technological change the perspective elaborated in biology by about punctuated discontinuity: like in the process of biological punctuation, the critical event is speciation, the application of existing technological know-how to a new domain. The new domain differs from the original one and this favors additional changes in a new direction. Eventually the new technology is so successful that it can invade other niches, including the original domain. The analysis of Mokyr synthesizes and puts in a broader perspective many years of empirical and theoretical research, which confirms the discontinuity of technological change and hence economic growth.

According to Mokyr much recent thinking among historians of technology and economists of innovation favors the basic notion of punctuated gradualness: radical inventions, stemming from recombination, raise the marginal product of effort in development, and lead to a sequence of further improvements. Consequently an intensification of smaller inventions can be observed in periods following radical inventions. Mokyr, borrows from the recent results of new advances in paleontology and population genetics and provides an interesting specification and interpretation of discontinuous technological change.

His approach stresses the interactions of radical and smaller innovations with a conducive environment: “The clustering phenomenon of radical innovations is widely observed in all cultural processes, and represents a combination of conducive environment and interactions between the agents themselves. In biology, the agents do not respond to mutations in other species directly, yet each species takes changes in others as changes in its environment. These interactions, too, may result in critical mass situations leading to occasionally intensive and sudden outbreaks of specification” (Mokyr, 1990, p. 352).

Levinthal (1998) has applied the punctuated approach to the analysis of the development of wireless technology from a laboratory device, to wireless telegraphy, broadcast radio and finally wireless telephony to convincingly show how the sequential applications of a given technological know-how to new domains with specific and heterogeneous characteristics generated a cascade of seemingly discontinuous changes, which in fact are the result of the same know-how gradually enriched in different directions by the stimulations of different contexts of application.

In a similar vein Loch and Huberman (1999) have elaborated a model of punctuated diffusion. This model is based upon three parameters: the rate of technological improvement of technologies, the level of positive externalities generated by their adoption and the level of switching costs of adopters. Technologies coexist and are characterized by different rates of technological improvements and different rates of generation of network externalities in a population of adopters that are heterogeneous with respect to the levels of switching costs. In this model the resilience of old, inferior technologies, as well as the sudden switch of all adopters to the new technology may depend on small changes in the parameters of the three interacting variables.

Building upon Gould's punctuationism one can argue that Marshallian gradualism and Schumpeterian saltationism are placed as extremes along a continuum of possibilities. As a matter of fact, it can be argued that Marshall and Schumpeter provide complementary, rather than conflicting, ingredients, useful to elaborate a broader, system dynamics system approach. Marshall emphasizes the role of out-of-equilibrium dynamics based upon technical and pecuniary, positive and negative externalities, as key factors in a process of increasing division of labor[3]. Schumpeter focuses the endogenous dynamics of intentional introduction of technological and organizational innovations, as determined by the rivalry among firms in product markets. These two strands of analysis can be brought together in an integrated dynamic framework based upon the methodology of systems dynamics. Gradual and discontinuous growth emerge as extreme cases of a broader punctuated process where innovation is induced by the mismatch between plans and expectations and it is fed by the changing access conditions to knowledge commons and by the effects of population dynamics on the costs and on the productivity of innovation activities.

The advent of new information and communication technologies has provided large evidence on both the discontinuity of technological change and the systemic complexity of the relations among technological innovations. Technological systems emerge in leaps and bounds as a result of a major scientific breakthrough and the introduction of a flow of minor technological innovations that are all related each other by strong elements of complementarity and cumulability in a few and selected regional and economic sites. The introduction and diffusion of new information and communication technologies has not been and still is not a homogeneous, ubiquitous and steady process across time and economic space. On the opposite, new information and communication technologies provide clear empirical evidence about a strong variance in time and space in the rates of generation of new knowledge, in the rates of introduction and diffusion, and in their effects, across regions, industries, product characteristics and firms.

The study of the introduction and gradual build-up of the technological system, centered upon new information and communication technologies, confirms the key

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[3] See Marshall (1920:368):"…nothing of this is true in the world in which we live. Here every economic force is constantly changing its action, under the influence of other forces which are acting around it. Here changes in the volume of production, in its methods, and in its costs are ever mutually modifying one another; they are always affecting and being affected by the character and the extent of demand. Further all these mutual influences take time to work themselves out, and, as a rule, no two influences move at equal pace. In this world therefore every plain and simple doctrine as to the relations between cost of production, demand and value is necessarily false."

role of the complementarity of an array of minor innovations, mainly based upon learning processes and tacit knowledge acquired in repeated learning processes in doing, in using and in interacting. The empirical evidence on the new technological system also confirms the key role of networking activities among learning firms. Complementarity among innovations in fact is mainly the result of a complex process of knowledge interactions and transactions among firms finalized to enhance the systemic scope of application and integration of each single small technological change.

Three elements characterize the emergence of Schumpeterian discontinuities in the new punctuated evidence about information and communication technological change: a flow of small and incremental innovations, characterized by high levels of complementarity, cumulability and fungeability; systematic networking activities by firms in the attempt to take advantage of the scope for system integration; and a conducive environment providing easy access to large flows of knowledge communication. The flow of small innovations can generate a quantum jump without a radical invention, but only within a conducive environment, able to support the necessary flow of incremental innovations.

The economics of localized technological change provides an appropriate analytical context to understand the mechanisms at work in the interaction between individual action and population dynamics.

## 3.THE ECONOMICS OF LOCALIZED TECHNOLOGICAL CHANGE

### 3.1. THE GENERAL CONTEXT

In the localized technological change tradition of analysis firms occasionally are faced with a mismatch between plans and actual market conditions. Firms can face unexpected changes in their product and factor markets either changing their technologies or their techniques. The mismatch is determined by the bounded rationality of firms that are not able to foresee all the possible changes that are likely to take place within the life horizon of their irreversible inputs.

The introduction of technological innovations by suppliers and competitors is a strong cause of the mismatch. Firms are unable to foresee all the possible technological changes that will be introduced in the market place and yet are forced, at each point in time, to make irreversible decisions about their tangible and intangible production factors.

Firms can adjust passively to new market conditions moving on the existing map of techniques. Alternatively, they might consider the introduction of new technologies. Irreversibility of tangible and intangible production factors limits the possibility to change the technique. The changes in techniques in fact require that each firm is able to move on a given map of isoquants. Because of the effects of irreversibilities and limited knowledge however technical changes engender some switching costs and some costs in terms of missing opportunities for learning. The introduction of new technologies is a viable alternative when switching costs are high and technological opportunities are good. Localized learning provides the opportunity to introduce new technologies, although in a limited technical space. The introduction of new technologies however is not free: it requires dedicated resources and specific activities must be carried out. A trade-off between technical change and technological change emerges whether to change just the technique, in the existing map of isoquants or changing the technology and hence the shape of the isoquants. The trade-off will be tilted towards the introduction of technological changes when the access to knowledge is easy and conversely switching costs are huge (Atkinson and Stiglitz, 1969; David, 1975; Antonelli, 1995).

Because learning is the main source of new knowledge and learning is mainly local, and because of the irreversibility of production factors and layout, technological change is inherently localized. It is induced by changes in factor and product markets that cannot be accommodated by technical changes in a given map of isoquants and the related price and quantity adjustments. Hence it is constrained by irreversibility and based upon the localized opportunities for learning and generating new knowledge (Antonelli 1999, 2001).

In Diagram 1 we see that a change in relative factor price affects the viability of previous equilibrium $E_1$. The firm can either change the technique and move to $E_2$ or change the technology by means of the introduction of technological innovations, so as to find a new equilibrium in the proximity of the isocline O $E_1$, in $E_3$ or (possibly) beyond.[4] The outcome will depend upon the levels of switching costs, that is the amount of resources that are necessary to perform all the activities to move from $E_1$ to $E_2$, compared to the amount of resources that are necessary to innovate and move towards and beyond $E_3$[5].

The resilience in the old equilibrium point $E_1$ is out of question: the firm produces at costs that are well above the levels of other firms, typically new firms with lower levels of irreversible factors, that are able to produce in the new equilibrium point $E_2$.

DIAGRAM 1: THE TRADE-OFF BETWEEN TECHNICAL CHANGE AND TECHNOLOGICAL CHANGE

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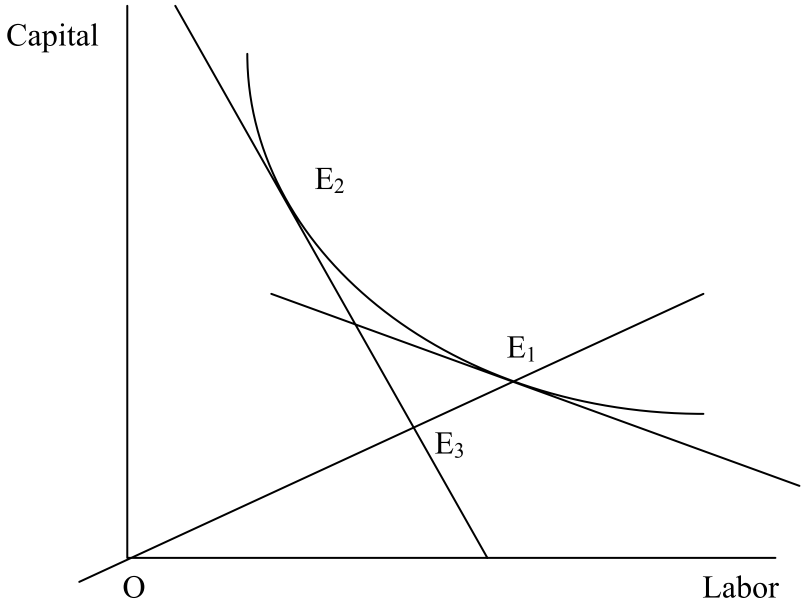
[4] Actually only new solutions beyond $E_3$ can engender an actual increase in total factor productivity (See Antonelli, 1995 and 1999)

[5] See Antonelli (1995 and 1999) for a rigorous exposition.



The firm is now exposed to a clear decline in the levels of performances and of satisfaction. A reaction is necessary: it can be a passive one consisting in the traditional technical change defined as a movement in the space of existing isoquants or a more creative one so as to include a change in the routines and the eventual introduction of innovations. The difference between current profits, after the changes in the marketplace, and the profits that should have been possible without such changes, measures the amount of resource the firm is ready to commit in order to bring about the changes that are likely to restore the expected levels of profitability.

In other words, because of the mismatch between expectations and the actual conditions in the markets place, the firm cannot rest in the position that had been planned. A budget for adjustment costs has to be allocated when the mismatch arises. Consequently it is clear that: i) the larger is the mismatch, the larger must be the budget available; ii) the larger is the flow of technological innovations being introduced in the markets for inputs and products, the larger is the mismatch for each firm.

All adjustments are possible but are costly. Technical change in fact, because of irreversibility of existing production factors and limited knowledge about the existing techniques, requires some switching activity. The introduction of technological innovations is a viable alternative to technical change. By definition, technological change on the other hand, is not on the shelf and its introduction in turn requires some innovation activities.

The position of the frontier of possible adjustments is defined by the amount of resources R that the firm should invest just to move from the previous equilibrium technique to the new one, either on the existing map of isoquants or in a new map. The search for the correct solution is identified as a maximization process where the firm tries and maximizes the amount of changes, including technological innovations, which can be generated with a given amount of resources set by the levels of switching costs[6].

The firm can identify the correct solution by means of the standard maximization of the output, with a given frontier of possible adjustments, when a proper isorevenue is defined. The isorevenue is defined by the absolute levels of the revenue generated by all adjustment activities consisting in the revenue made possible by the introduction of new techniques and the revenue made possible by the introduction of the new technologies respectively. Formally we see the following relations:

$$(1)\quad TC = b\,(R)$$

$$(2)\quad SW = c\,(R)$$

In equation (1) TC measures the amount of technological innovation, necessary to change the technical space, that the firm can generate taking into account the internal competence and knowledge accumulated and the external knowledge it can access. Its unit of measure is provided by the geometric distance on the isocline between the new isoquant expressing the new technology and the existing isoquant (see Diagrams 1, 2 and 4). In equation (3) SW defines the amount of technical change necessary to move in the existing technical space and reflects the levels of irreversibility and rigidity of tangible and intangible capital. Its unit of measure is provided by the geometric distance between equilibrium points on existing isoquants (see Diagrams 1, 2 and 4).

Much work has been done in the localized technological change approach, to inquire into the conditions, characteristics, and determinants of the trade-off between technical change and technological change. The introduction of technological changes is possible only if appropriate amounts of knowledge and competence, both internal and external to firms, has been accumulated and is available to firms. The conditions of the learning processes and the determinants of the eventual production of knowledge have received much attention. The costs of technical change, on the other hand, are influenced by the irreversibility of the commitments made by firms and the costs of adjusting fixed production factors, both tangible and intangible, to new and unexpected product and factor markets.

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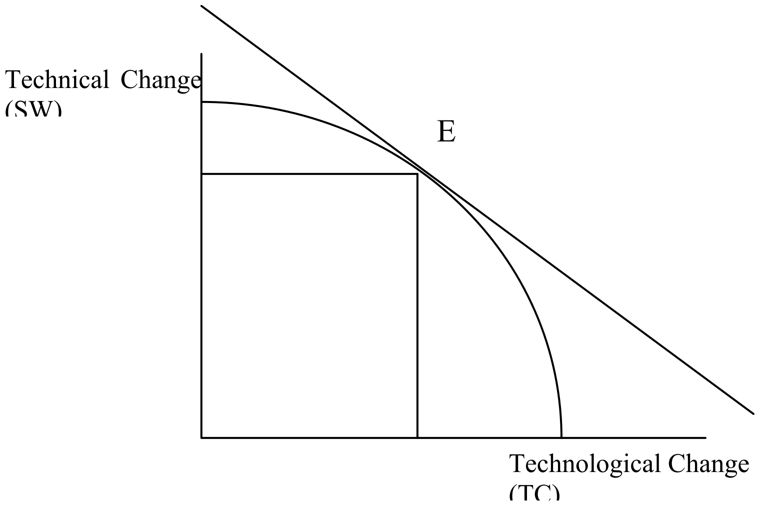
[6] The firm can ‘discover’ to its surprise that the equilibrium amount of possible adjustments makes it possible to introduce a total factor productivity increasing technological change which leads the firm beyond equilibrium point $E_3$ (See Diagram 1). This is clearly a case for procedural rationality as opposed to substantive rationality (Simon, 1982).

It is clear that the relationship between switching –i.e. changing the technique- and innovation – i.e. changing the technology- is essential to define the outcome of the search process initiated by the changes in the product and factor markets. It seems clear that the larger is the efficiency in the production of technological changes and the lower the efficiency of switching, the larger the amount of innovations introduced. Correspondingly, the smaller is the efficiency of research activities and the smaller will be the amount of innovations each firm will generate. The firm will adjust to the new factor and product market conditions more by means of switching activities than by means of the introduction of new technologies.

The extent to which the firm will rely on either switching or innovation will be influenced by the relative efficiency of either activities and by the shape of the relevant isorevenue. This is well represented by the shape of the frontier of possible adjustments.

DIAGRAM 2: THE FRONTIER OF POSSIBLE ADJUSTMENTS



To make this point more compact, let us now assume that a frontier of possible adjustments can be considered, such that for a given amount of resources (R) necessary to face the mismatch, firms can generate an amount of either technological change (TC) or technical one (SW). Specifically the shape and the slope of the frontier of creative adoptions reflects the effects of the technological opportunities based upon the localized competence built by means of internal learning by doing and the opportunities offered by the knowledge and the technologies generated by third parties that become available either through imitation or by means of the active push of upstream suppliers. Formally this amounts to saying that:

$$\textbf{(3) SW = d (TC)}$$

In order for standard optimization procedures to be operationalized, a isorevenue function needs to be set. The revenue of adjustments (RA) compares the revenue that adjustments by switching in the technical space (SW) yield with respect to the revenue of technological change (RTC). Formally we see:

$$(4)\quad \mathbf{RA = s\ SW + t\ RTC}$$

where s and t measure the unit revenue of switching and the unit revenue of technological change generated with the given amount of resources available to face unexpected changes in product and factor markets and the equilibrium amount of resources that can be identified to fund the introduction of technological change.

The system of equations can be solved with the standard tangency solutions so as to define both the mixes of creative adoptions, which in each specific context firms are advised to select and the amount of technological change with respect to switching the context suggests selecting. The equilibrium conditions is in fact:

$$(5)\quad \mathbf{d'\ (TC) = t/s}$$

The equilibrium conditions identified by equation (5) capture the essence of localized technological change consisting of creative reactions engendered by the mismatch between plans and actual factor and market conditions for firms that are constrained by the irreversibility of their choices.

## 3.2. COLLECTIVE KNOWLEDGE

Firms are induced to change their technologies by the mismatch between plans and actual market conditions and the emerging losses stemming from irreversibility. Firms can innovate, however, only if they are able to command appropriate levels of technological knowledge. According to the acquisitions of the localized knowledge approach, the firm cannot be seen as the single actor in the process of generation of new knowledge.

Localized technological knowledge is the result of four specific activities: learning, socialization, recombination and research and development. These activities are complementary and none can be disposed of. A limited substitution, however, can take place among them. Much empirical work has investigated the determinants of the efficiency of the activities leading to the generation of new knowledge and the eventual introduction of new technologies. The evidence has stressed the role of both internal and external ingredients. Next to the characteristics of the internal organization and structure of firms, a long list of external factors play a major role:

the structure of the local systems of innovations; the channels of communications among firms and between them and scientific institutions; the forms of interactions and cooperation between firms active in the same industry as well as across industries and diverse markets; the working of labor markets as vehicles for the transmission of information and knowledge; the management and the structure of the relations among users and producers; the positive and negative effects of the spillover of proprietary knowledge among rivals; and more generally the governance of the appropriability conditions and the structure of intellectual property rights (Antonelli, 1999, 2001, 2003).

The complementarity between internal and external knowledge plays a key role in this context. The variety of firms and learning institutions are mostly important in the generation and circulation of knowledge when the latter is viewed as a collective good, with varying degrees of appropriability, is dispersed and fragmented in the economic system, and is the result of both top-down and bottom-up processes, and when learning by doing, learning by using and learning by interacting with suppliers, customers and rivals play an essential role together with intramural research and development activities.

Knowledge is currently increasingly viewed as a collective process. The notion of collective process differs both with respect to the Arrovian tradition of knowledge as a public good and the approach to knowledge as a quasi-private good, implemented by new growth theory. Collective knowledge is a shared activity that can be implemented only by interactive agents that belong to a community of action and understanding. Collective knowledge pays attention to the consequences of knowledge indivisibility and the role of the complementarity among the localized bits of knowledge possessed by each agent that characterize both the generation and the dissemination of knowledge in the system and value the contribution of external knowledge into the production of new knowledge. In this approach the role of technological communication among learning agents is stressed as a major systemic character affecting the actual capability of each agent to implement its internal knowledge (Allen, 1983 and Von Hippel, 1988).

The network structure of knowledge communication networks affects deeply the flows of knowledge communication and hence the actual availability of external knowledge. There is an array of possible network architectures. In geodesic networks, i.e. networks where each agent has a direct link to each other agent, communication costs are very high: the dissemination of new knowledge is hampered by relevant communication costs and by the decay of knowledge spillovers associated with distance and heterogeneity among agents. Within centered networks based upon many interconnected and hence competitive hubs, knowledge is disseminated far better than in fragmented networks, where only a few links connect scattered clusters or in networks based upon monopolistic hubs able to exert a control upon knowledge flows and to extract rents out of it.

The appreciation of the external conditions for the generation of localized technological knowledge is an important result of this line of enquiry. Localized technological knowledge, in fact, is the result of the combination of internal competence and knowledge with the external knowledge embodied in capital goods and intermediary inputs provided by upstream suppliers or available in the form of technological information, licenses and patents and technological spillovers and made available respectively by means of technological transactions and technological interactions. The relationship between external and internal knowledge is crucial.

The role of communication and transmission of knowledge is a major factor assessing the rate of generation of new knowledge and introduction of new technologies. Systems differ with respect to the speed and capillarity of the flows of knowledge communication. Percolation analysis - borrowed from physics- and communication theory have provided the basic tools to appreciate the distinctive role of receptivity and connectivity in communication processes. The receptivity of agents and their absorptive capabilities are now appreciated as well as the strength and intensity of the message receives due attention (Cohen and Levinthal, 1990). The structure of economic systems is analyzed from the viewpoint of the knowledge communication flows, the density and duration of the communication channels in place and their organization within the networks of relations. Knowledge communication in fact is not spontaneous, but on the opposite, it is the result of intentional and dedicated networking activities.

In the economics of localized technological knowledge and localized technological change, knowledge networking is an essential component of the broader basket of research activities. Knowledge networking is the result of both the exploration and search for the sources of external technological knowledge, either tacit or codified, and of the intentional direction of internal research and learning activities towards complementary external knowledge. Knowledge networking includes: a) knowledge transactions, that is the purchase of knowledge in the markets for technological knowledge where prices are incomplete vectors of information, b) cooperation among firms based upon an array of contractual forms such in-house outsourcing, technological clubs, patent ticketing, joint-ventures, sponsored spin-off, open technological platforms and c) knowledge interactions that are not mediated by prices but rather based upon proximity in geographic, industrial and knowledge space, constructed trust and reciprocity. Knowledge networking is strictly complementary to internal learning and intramural research and development activities.

Much empirical evidence however also confirms that the efficiency of resources invested in internal research activities depends upon the amount of external knowledge available, made accessible by means of networking activities and complementary with dedicated efforts. In turn the levels of external knowledge are influenced by the number of firms engaged in complementary research activities and the extent of their research budgets. The notion of supermodularity introduced by Milgrom and Roberts (1995) apply usefully to knowledge and provides a useful tool to grasp the dynamics of knowledge complementarities. Knowledge is supermodular when raising the internal research increases the returns to networking and viceversa.

## 3.3.THE DYNAMICS OF LOCALIZED TECHNOLOGICAL CHANGE WITHIN KNOWLEDGE COMMONS: NETWORKING AND SPILLOVERS

The dynamics of localized technological change is grasped when it is recalled that the amount of the resources that become available to fund the adjustment to the mismatch is endogenous and dynamic, as well as the efficiency of the resources invested in the research activities. This amounts to say that both the shape and the position of the frontier of possible adjustments (See Diagram 4) are endogenous and dynamic[7].

Building on the previous analysis two elements must now be stressed.

First, a cumulative inducement mechanism is at work because the localized technological change introduced by each firm at time t is the main, if not the single, cause of new and increasing mismatch between their own plans and their actual product and factor market conditions for other firms at time t+1. Specifically we shall assume that the general amount of mismatch increases more than proportionately: the new localized technologies introduced by each firm shall disturb the correspondence between plans and facts for more than one firm. Formally this amounts to say that the number of firms confronted with the mismatch and hence the choice between switching and changing locally the technology, at each point in time, is larger than the number of firms found in the same conditions in the previous period of time:

$$(6)\quad \mathbf{N_{t+1} = j\,(N_t)}$$

With $j' > 0$ and $j'' = 0$

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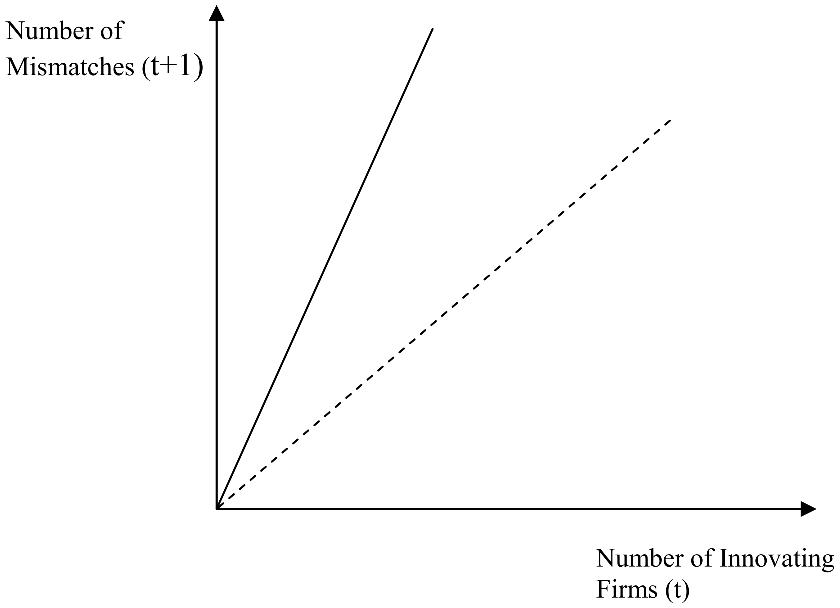
[7] We shall assume that the unit costs and the efficiency of switching activities are not influenced by relevant externalities.

**INSERT DIGRAM 3 ABOUT HERE**
**THE CUMULATIVE INDUCEMENT MECHANISM**



Therefore as the mismatch increases, a larger budget for adjustment costs has to be allocated. Consequently it is clear that the levels of the adjustment budget at each point in time can be considered a function of the amount of innovations introduced in the previous period of time. The levels of the adjustment budget at each point in time can be considered a function of the amount of innovations introduced in the previous period:

(7) $R_{ti} = a\,(I_{t-1})$ where $a' > 0$ and $a'' > 0$

Where $R_i$ measures the budget for adjustments at time t that are made necessary for each firm to manage the mismatches stemming from the amount of innovations (I) introduced in the previous period of time. The number of the destabilized firms at each point in time by the innovation introduced in the previous one is also increasing over time. Moreover the shape of the relationship expresses a dynamics where the introduction of each innovation generates a more than proportionate increase in market entropy for the other firms. The mismatch between plans and actual market conditions in fact is not exclusively determined by the introduction of technological innovations but it is clearly augmented by innovations introduced at each point in time.

Second, firms do not innovate in isolation, but rely upon knowledge pools. Knowledge networking however is not free. It requires dedicated resources. Much empirical evidence confirms that the unit costs of search activities, including networking activities, are influenced by the number of firms engaged. A clear negative, pecuniary externality is at work here.

Network analysis for social communication systems provides basic elements to understand the dynamics of communication costs. In a network the maximum number of links (ML) between the agents (n) is given by the following simple equation: ML = (n-1) n/2. Hence the increase of the number of agents in the network engenders a more than proportionate growth in the number of links. If coordination costs are associated to the number of communication links, it seems clear that communication and coordination costs increase more than proportionately with the size of the network (Wasserman and Faust, 1994). Much anecdotic evidence about the dynamics of coordination and communication costs within industrial and technological districts confirms that congestion problems do emerge rapidly with the increase in the number and in the variety of agents that participate (Bresnahan and Gambardella, 2005; Patrucco, 2005).

This amounts to articulate the specification of equation (1) with the following system of equations:

$$(8)\ TC_{ti} = e\ (A_{ti}(R_{ti}))$$

The amount of technological change that each firm can generate at time t depends upon the general level of efficiency ($A_t$) of its research function and upon the amount of resources invested in research activities by each firm i ($R_t$).

The level of actual research budgets, for given levels of resources available, depends upon the level of the unit costs for research activities r. The budget available for possible adjustments can fund a level of research and networking activities (R&N) necessary to valorize and mobilize the tacit knowledge acquired by localized learning processes, and to identify and internalize the external knowledge available. This depends on the levels of unit costs of research and networking activities (r):

$$(9)\ R = rR\&N$$

The unit costs of research, including networking, that are necessary to identify, internalize and integrate the external knowledge, depend upon the number of other firms (N) engaged in research activities and in the total amount of research activities at work:

$$(10)\ r = f(N * R\&D) \text{ with } f'>0, \text{ and } f''>0$$

The number of firms engaged in research and networking activities and the general levels of their research activities exerts also a positive effect in terms of the amount of external knowledge that becomes available to each firm by means of technological interactions, spillovers and technological externalities of different kinds. Hence

$$(11)\ A_{ti}= g( N * R\&D) \text{ with } g'>0, \text{ but } g''>0$$

The substitution of equations (9) , (10) and (11) into the former equation (8) leads to the fully specified form of equation (2):

$$(12)\ TC_{ti} = e ( g( N * R\&D)_{ti} ( f(N * R\&D) R_{ti}))$$

From equation (12) it is apparent that the amount of technological change that each firm can generate at time t is influenced by the positive externalities exerted by the external knowledge made available by the other firms and effects of the negative pecuniary externalities on the unit costs of research and networking activities. The relationship between equation (10) and (11) is crucial for assessing the dynamics of the system.

The relationship between positive and negative externalities, i.e. between knowledge spillovers and networking costs becomes crucial. The amount of technological change that a firm, induced to react by the mismatch between plans and facts, can generate is determined by three elements: i) the amounts of the resources available, ii) the unit costs of the activities that are necessary to valorize the internal learning processes, to make explicit the tacit knowledge accumulated and to access, by means of networking, the external knowledge available; iii) the amount of spillovers and external knowledge that can be internalized and their actual complementarity.

Specifically two forces are at play here: the negative effects of pecuniary externalities on the costs of generating new localized technological change, and the positive effects of knowledge supermodularity. More specifically the effects of the positive and negative externalities are well grasped by the analysis of the derivative of TC (the amount of technological change that each firm is able to generate) with respect to N (the number of firms engaged in the same knowledge common):

$$(13)\ dTC/dN = [g'(N * R\&D)(dN*R\&D + N*dR\&D) + (f'(N*R\&D)(dN*R\&D + N * dR\&D) R)]\ 1/dN$$

The value of the ratio of the first to the second term of equation (13) conveys all the relevant information. The first terms expresses the positive effects of the number of firms engaged in the same knowledge common in terms of access to same collective knowledge and hence in terms of positive externalities, while the second measures the negative effects in terms of pecuniary externalities. The value of the ratio can be positive, negative or equal to zero:

$$(14)\ g'(N*R\&D)(dN*R\&D+N*dR\&D)/(f'(N*R\&D)(dN*R\&D+N*dR\&D)R) = \begin{cases} 0 \\ <0 \\ >0 \end{cases}$$

Three cases can be identified.

A) Fragmented knowledge. Networking costs are very high and the effects of knowledge supermodularity are poor. Technological knowledge exhibits low levels of supermodular complexity as the single bits of knowledge are not complementary. Each of them is the result of idiosyncratic research and learning activities, internal to firms and specific to their conditions. When the negative effects of networking costs are always larger than the positive effects of knowledge supermodularity, firms will rely on external knowledge, only to a limited extent. Networking activities will be kept at a minimum. Technological change is occasionally introduced by firms in isolation. This situation can be considered the standard case, consisting with textbook microeconomics where firms are allowed only to change their techniques and are not able to change their technology.

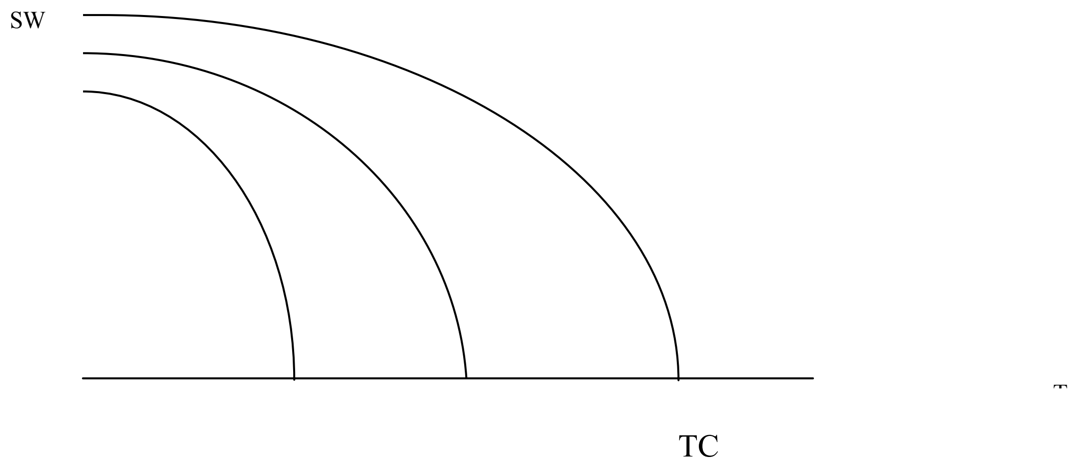
B) Positive feedbacks. The second case takes place when both the effects of positive and negative externalities exhibit a negative derivative with respect to the number of firms engaged in the knowledge common. Their effects increase less than proportionately with the number of firms engaged. The derivative of pecuniary externalities, however, is smaller than the second derivative of technical externalities. In this case the dynamics is fully endogenous as the feedback of the introduction of innovation on the adjustments budgets keep exerting their positive effects that translate into larger and larger amount of research activities being conducted. At each point in time the flow of innovations is larger than in the previous one, as well as the efficiency of research activities is larger and the unit costs of research skills keep increasing albeit at a lower rate than that of the increase of the efficiency. The number of firms engaged in research and networking activities keeps growing as the growing number of innovations being introduced destabilizes an ever-increasing number of firms.

The position and the shape of the frontier of possible adjustment will change so as to reflect both the larger size of the both intercepts and the larger, relative, efficiency of research and networking activities with respect to switching ones. With a given slope of the isorevenue it is clear that the smaller is the marginal rate of transformation of switching activities into research activities and the large the equilibrium value of technological changes being introduced at each point in time. Much theorizing about new growth theory can be accommodated within this special case.

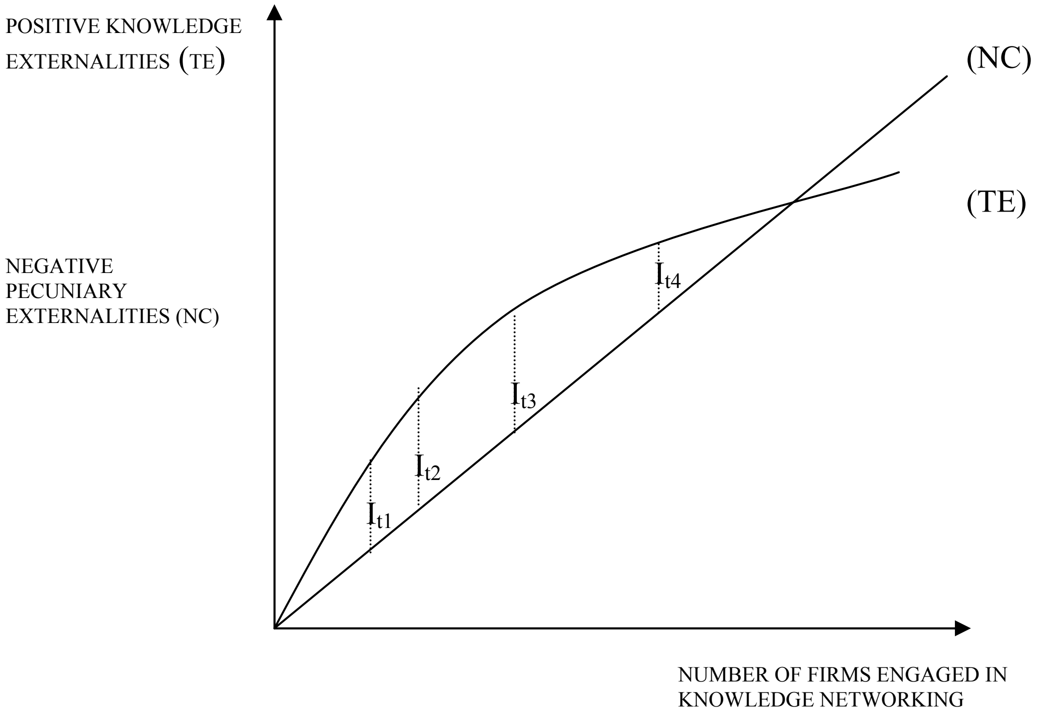
C) Localized supermodularity. The third case is the most interesting. It is a case of endogenous but transient net positive externalities: external increasing returns stemming from knowledge supermodularity do take place but within a localized and limited context. The fabric of communication channels in place and the endowment of social capital –including the quality of the local scientific infrastructure- and the levels of knowledge supermodularity are such that the potential complementarity among the knowledge base and the competence and the stock of knowledge of diverse firms can be identified, implemented by means of effective networking and well focused research activities and fully exploited. Commons of collective knowledge take-off. This dynamics however takes place only within a circumscribed region of technological knowledge and for a limited number of firms when the second derivative of positive externalities is positive and the second derivative of negative externalities in non-negative (See Diagram 5).

As long as the positive effects of knowledge externalities, in terms of spillovers and access to external knowledge, are larger than the negative effects of pecuniary externalities in terms of increased networking costs, the number of firms engaged in building complementary knowledge will increase. The amount of innovations being introduced at each point in time will be larger, with respect to the previous period. Moreover in the following period the amount of the mismatch will be larger and hence larger the budget made available to face the new necessary adjustments. As long as the positive effects of knowledge externalities will be larger than the negative effects of pecuniary externalities, the larger budgets for adjustments will translate into larger flows of innovations being introduced into the system. The size of the knowledge common will increase as long as net positive externalities exist. The number of networking firms will keep increasing as well as the flow of complementary innovations being introduced.

INSERT DIAGRAM 4 ABOUT HERE: THE CHANGING SLOPE AND POSITION OF THE FRONTIER OF POSSIBLE ADJUSTMENTS



INSERT DIAGRAM 5 ABOUT HERE
THE DYNAMICS OF KNOWLEDGE AND PECUNIARY EXTERNALITIES FOR RESEARCH ACTIVITIES



Specifically, the negative effects of pecuniary externalities in terms of the increase of the unit costs for research and networking activities on the one hand and the positive effects of collective knowledge, in terms of the increase in the output of research activities on the other, can be isolated and directly confronted (See diagram 5). The increase of the unit costs of research activities is expressed by the positive and constant slope of research&networking costs (NC) as determined by the number of firms engaged in knowledge networking activities. The number of firms engaged in complementary research activities, within the same knowledge common, exerts also a positive, albeit decreasing, effect on the productivity of research activities conducted by each firm as it expressed by the loglinear slope of TE. The difference between the slopes of NC and TE is crucial:

**(15)** $TE = m(N)$, **with** $m'(N) > 0$ , $m''(N) < 0$
**(16)** $NC = n(N)$, **with** $n'(N) > 0$ , $n''(N) = 0$
**(17)** $p(N) = m(N) - n(N) \quad \text{s.t.} \quad m' > n'$

**it follows that** $p'(N) > 0$, **and** $p''(N) < 0$

Let us recall that as long as net positive externalities can be found, the number of new firms that engage in networking activities, within the same knowledge common, increases. Moreover the need to fund a budget for adjustments activities and hence to conduct additional research activities and the size of their adjustment budget – including research and networking activities- is a function of the flows of innovations introduced. Hence:

$$(18) \qquad dN(t)/dt = W(p(N))$$

given the properties of W and p(N) it follows that:

$$(19)\ N(t) = \S_t\,(dN(t)/dt)\,dt = \S_t\,W(p(N))dt$$

Equation (19) establishes a functional relationship between the flow of networking firms engaged in research and induced by the mismatch between plans and actual market conditions and the stock of collective innovators.

The p(N) function is S-shaped and has got a flexus. Therefore a functional form that is compatible with the specific conditions is:

$(20) N(t) = \alpha 1/ 1- e^{-kt}$ , where k measures the speed of the process[8].

Is now clear that the dynamics of the systems is determined by the feedback of innovations on the levels of mismatch and the interplay between positive and negative externalities. When the effects of positive externalities are slightly larger than the negative ones the dynamics of the system is smooth. When on the opposite the net positive externalities are large, the region of the inflection point of the S-shaped process has a strong projection of the vertical axis.

The speed parameter k in equation (20) plays a key role. Its value can be seen as the effects of two dynamic processes. First, the size of this relationship is augmented by the feedback between innovations and the resources for adjustments. The parameter a

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[8] Equation (20) equation has its solution in the standard logistic function.

of equation (7) here plays a key role. When the feedbacks of innovations on the budget for adjustment activities in the following period are large, the slope of the S-shaped process is large as well as the saturation limit. Conversely, when the flows of innovations introduced in the previous period of time has only a small positive effect on the budget for adjustments activities funded in the following period of time, the S-shaped process remains defined within a small region with low levels of innovation activities and hence small flows of innovations being introduced. Second, the rates of growth of the mismatch generated by other innovations and hence the rates of entry of new firms into the knowledge commons where net externalities are positive, matter: firms are clearly able to search and to move in the knowledge space (Marchionatti, 1999)[9]. The parameter j of equation (6) here plays a key role. The mobility in knowledge space of firms, albeit limited by the localized roots of their competence, has the twin effect to speed up the rates of generation of technological change and to affect the shape and the architecture of knowledge networks. The rates of technological change, as long as fertile knowledge commons are generated by the interplay between positive and negative knowledge externalities, will be determined by the catalytic reaction stemming from the interaction between innovation, mismatch and collective creativity.

When the positive effects of knowledge externalities will match the negative effects of pecuniary networking externalities, the unit costs of innovations will no longer decline. Firms will rely less and less on networking and hence on external knowledge in order to generate new localized knowledge. Internal research and learning activities of single firms will play a larger role. Technological change is now characterized by a flow of smaller, incremental and discrete technologies.

At this time, the number of innovations being selected by firms facing adjustments problems and eventually introduced, will be smaller than the ones introduced in the previous period of time. The system will not, however, enter a stationary state, because of the exponential relationship between innovations and mismatch and hence resources for possible adjustments.

When the attention is focussed upon the rate of innovation it is clear that the dynamics is shaped now by the relationship between the dynamics of the unit costs of innovations and the dynamics of the budgets available to fund innovations. The introduction of radical inventions here is not necessary for the dynamics of the process to be sustained if, the amount of the resources generated by the mismatch, keeps growing and consequently the shape of the frontier keeps moving towards the right, albeit with a changing and less favorable slope (Mokyr, 1990).

The analysis of the dynamics of positive and negative externalities, framed in the context of the economics of localized technological change, confirms that

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[9] Intentional mobility of agents in relevant topological spaces matters for complex dynamic system analysis where often agents are allowed to change their location only at random (Rosser, 2004).

Marshallian gradualism and Schumpeterian saltationism can be reconciled when a sequence of small, incremental, but cumulative innovations takes place in a conducive context where a catalytic and collective process of creative reactions, augmented by a conducive population dynamics, becomes the engine of endogenous changes in the shape and the position of frontier of possible adjustments and leads to punctuated leaps that shape the path of technological change and economic growth, both in terms of rates and directions.

## 3.4. THE DYNAMICS OF COLLECTIVE KNOWLEDGE AND LOCALIZED TECHNOLOGICAL CHANGE: ANNECDOTAL EVIDENCE IN PIEDMONT

The long-term growth of Piedmont, in northwestern Italy, provides large evidence about the key role of collective knowledge and localized technological change in the punctuated technological and industrial development of a region (Castronovo, 1971; Bairati, 1983). Industrial and technological change in Piedmont in the XIX and XX centuries is characterized by a sequence of discontinuous phases of rapid growth centered upon different and yet interrelated technologies (Amatori and Colli, 1999; Catronovo, 1995, Barca, 1997). The displacement of the capital city of the new Italian Kingdom, in 1865, away from Turin, to Florence and eventually to Rome, impoverished the region, but left a remarkable endowment in terms of technological and scientific institutions, able to provide advanced technological services useful not only for the implementation of the aggressive military sector but also for the business community. The introduction of hydroelectric power was largely due to local scientific capabilities based upon the group guided by Galileo Ferraris at the Politecnico, the school of engineering of the University of Turin, which eventually acquired full institutional and academic autonomy. The Politecnico itself was in fact the eventual outcome of the merging of the Royal Arsenal and of the Royal School of Artillery where for centuries the command of engineering had been implemented for military purposes. The introduction of hydro electrical energy can be considered the result of a localized search for innovation strongly determined by the attempt to react to the crisis engendered by the displacement of the capital city –a typical failure-induced reaction- by mobilizing the local intangible endowments in terms of collective knowledge and to make good use of the local tangible endowment of an alpine region. It succeeded and provided large investment opportunities to a mountain region with several valleys and rivers: a large number of dams was built, many companies entered the industrial production of energy and upstream in the production of electrical machinery. Energy prices fell sharply. The textile industry benefited from the large supply of cheap energy and in turn generated a large demand for textile machinery. The engineering industry grew exponentially in the years between the end of the XIX century and the beginning of the XX century. The scientific traditions of the Politecnico and the rapid growth of the technological capabilities of the local engineering industry provided major opportunities to contrast the eventual decline of the textile industry and to take advantage of the technological opportunities in the car industry. The birth of the automobile industry in Italy, centered in Turin, provides one of the clearest historical examples of a highly specialized technological district characterized by a typical S-shaped growth. In the period 1896-1928, 167 car companies were born in Italy, almost 40% of which, i.e. 66 car companies, were born in Piedmont. After Piedmont, Lombardy, almost three times as large in terms of size of population and economic activity, was the second region with 63 new car companies. In the rest of the country, only 38 companies were created. Entry in the car industry in Piedmont follows in these thirty years a typical S-shaped process: after a few years of slow growth with 2 or 3 companies per year, the typical flexus takes place in the years 1904-1906 when 21 companies are created: 4 in 1904, 10 in 1905 and 7 in 1906. After 1906 the process slows down in Piedmont and spreads slowly to the rest of the country. Eventually a district champion emerged and internalized systematically the complementary activities with a clear substitution of internal hierarchy to external coordination. Much empirical evidence provided by economic historians confirms the key role of collective knowledge in such a process: mobility of skilled personnel especially played a key role, both between the Politecnico and the business community and among firms. A web of cooperative forms is documented especially in user-producers relationships with the creation of open technological platforms to which firms could contribute their distinctive competence to larger projects. Increasing levels of specialization and the abundant supply of local advanced suppliers of machinery, specifically machine tools, are recorded as a major conducive factor (Antonelli, 2001). The increasing problems experienced in the dynamic coordination of such a fast growing industry with large numbers of competing and yet cooperating firms are documented as a cause for the eventual consolidation of the industry and the decline in the rates in technological innovation. The sequence of bursts of phases of technological and industrial change experienced in Piedmont for almost a century can be easily interpreted in terms of a punctuated sequence of applications of a given technological know-how to a sequential string of new and yet related domains. At each point in time when the technology generated by means of the prior application to a new domain entered a period of decline, with evident downturns in the rates of profitability and performances, new failure-induced attempts of localized applications of the technological competence so far acquired, in new, but adjacent technological domains were made. A flow of localized technological changes were introduced and paralleled by the gradual emergence of new knowledge commons fed by the interactions among a variety of innovating firms in a conducive institutional context based upon the strong scientific traditions of the local environment. As a result, a new wave of industrial and technological growth took place, with sustained S-shaped rates of technological change and industrial growth, fed by the entry of new firms and the introduction of incremental innovations by incumbents, in the window of time in which the positive effects of knowledge supermodularity were not offset by the increase in unit costs of external coordination within knowledge commons. In the Piedmontese case we see the first step from military engineering to electrical engineering, then followed by applications in textile production and eventually in textile engineering, then from textile engineering to machine tools, and finally from machine tools to the car industry. The last step from mechanical engineering into electronics and telecommunication failed at the end of the XX century with the collapse of a number of key firms. The severe economic difficulties of the regions in the passage from the XX to the XXI century can be identified in the weakness of the link between mechanics, electronics and new information and communication technologies, still missing or not yet fully implemented.

## 4.CONCLUSIONS

The economics of localized knowledge and localized technological change provides an analytical framework that can easily accommodate the dynamics of punctuated growth and continuous change. The key element is provided by the endogeneity of technological change. The appreciation of the role of positive and negative externalities and of the relationship between innovation and mismatch makes clear that the position and the slope of the frontier of possible adjustments are both endogenous and dynamic.

The dynamics of the system is generated by the interplay between the effects of knowledge complementarity and networking costs. In turn networking costs are very much determined by the endowment of communication channels, both tangible and intangible, of each economic system.

Economic systems with a poor knowledge communication infrastructure, low levels of trust and social capital, high levels of opportunistic behavior have high levels of knowledge networking costs. For given levels of knowledge complementarity, networking costs are very high. Firms rely mainly on internal knowledge and have not access to pools of external knowledge. For given levels of mismatch and hence resources for either technical or technological change, firms will introduce lower levels of innovations. The dynamics of the process here is fully determined by the feedback between innovations, mismatch and the amount of resources available for possible adjustments.

In economic systems with a rich knowledge communication infrastructure and a large endowment of social capital firms have low levels of networking costs and hence can easier access external knowledge available. The net positive effects of knowledge spillovers provide the system with the opportunity to introduce a sustained flow of innovations. Sustained rates of technological change take place as long as the increase of networking costs does not match the gross effects of technological externalities.

The accelerated generation of a myriad of small technological innovations is the consequence and the cause for the creation of new technological systems. Systemic integration of new technologies is in fact the result of intentional networking. Knowledge networking makes possible the valorization of complementarities among technological innovations. In turn systemic integration enhances the productivity of resources invested in research activities and this leads to further increase in the amount of resources available to fund innovation.

The policy implications of this analysis are clear. A knowledge communication policy can sustain accelerated rates of introduction of waves of complementary technological changes. Specifically we see that the lower are the costs to searching, accessing and internalizing reliable sources of external knowledge and the larger are the chances that a creative reaction as opposed to passive adjustment takes place to face the mismatch between plans and actual markets conditions.

A continuum of growth regimes can now be identified, according to the results of the interplay between positive and negative externalities. Punctuated growth is clearly a special case provided by the values of the second derivative of positive and negative externalities. Punctuated and gradual growth are simply two possible outcomes of a broader dynamic process governed by the interaction between irreversibilities, creativity and the characteristics of the systems in terms of connectivity and receptivity.

The tools of evolutionary biology can be successfully applied to economics when the effects of irreversibility and creativity are taken into account in a context where technological change is endogenous and the analysis is dynamic. The fruitful grafting requires that two types of feedback are accounted for. First, the interplay between innovation and entropy in the markets for products and for production factors and hence between innovations and extent of the mismatch those myopic firms need to face. Second the interplay between the context of action and decision-making for each agent and the characteristics of the system, in terms of knowledge communication flows.

Punctuated growth coincides with the emergence of collective knowledge, that is, the participation of a variety of learning agents into the generation of technological systems. Technological systems are characterized by high levels of endogenous knowledge complexity and fungeability such that the vertical and horizontal complementarity of knowledge is brought together. Latent knowledge complementarities, however, can be brought together and fully exploited only when the negative externalities engendered by networking costs are lower than the positive effects of knowledge externalities.

On these bases, Marshallian gradualism and Schumpeterian saltationism can prove to be not only compatible, but also, even more, complementary tools of a broader systems dynamics approach to modeling economic and technological change.

With respect to complex dynamics systems this paper has shown how relevant is, in understanding the dynamics of the process, the role of the intentional and strategic action of firms that are induced to change their technology and rely upon external knowledge, in terms of structural change. In so doing in fact firms search and move in the knowledge space and enter into specific knowledge commons. The topology of the knowledge space is changed by the strategic action of myopic firms, as much as the topology of the technological and industrial space is changed by the introduction of technological innovations. Firms are able to change the structure of the economic space and the architecture of knowledge networks.

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