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AN INTRODUCTION TO THE SYSTEM DYNAMICS OF TECHNOLOGICAL CHANGE: THE BASIC TOOLS

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AN INTRODUCTION TO THE SYSTEM DYNAMICS OF TECHNOLOGICAL CHANGE: THE BASIC TOOLS

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ABSTRACT. This Handbook presents a systematic attempt to show how building upon the achievements of the economics of innovation, an economic approach to complexity can be elaborated and fruitfully implemented. This introductory chapter articulates the view that innovation is the emergent property of a system characterized by organized complexity. It implements an approach that enables to provide economic foundations to analyzing the incentives of economic action and the notion of organized complexity. In this approach agents retain the typical characteristics of economic actors, including intentional choice and strategic conduct, augmented by the attribution of creativity. Economic agents are able to react to out-of-equilibrium conditions and may try and change both their production and their utility functions. The localized context of action and the web of knowledge interactions and externalities into which each agent is embedded is crucial to make their reaction actually creative, as opposed to adaptive, so as to shape the actual effects of their endogenous efforts to change their technologies and their preferences. In turn, the successful introduction of new localized technologies, changes the structural features of the system and hence the flows of knowledge externalities and interactions. This dynamic loop exhibits the characters of a recursive, non-ergodic and path dependent historic process. This approach enables to move away from the static, low-level complexity- of general equilibrium that applies when both technologies and preferences are static, as well as from the random variation of evolutionary thinking, and to grasp the system dynamics of technological change as an endogenous and recurrent process that combines rent-seeking intentionality at the agent levels with the appreciation of the knowledge externalities and interactions that stem from the organized complexity of the structural characters of the system.

KEY WORDS: CREATIVE REACTION, KNOWLEDGE EXTERNALITIES&INTERACTIONS, LOCALIZED TECHNOLOGICAL CHANGE, STRUCTURAL CHANGE, RECURSIVITY, PATH DEPENDENCE, COMPLEXITY.
JEL CODE: O33

1. INTRODUCTION

Complexity is emerging as a new unifying theory to understand endogenous change and transformation across a variety of disciplines, ranging from mathematics and physics to biology. Complexity thinking is a systemic approach according to which the outcome of the dynamic behavior of each agent and of the system into which each agent is embedded can only be understood as the result of interactions among heterogeneous agents embedded in evolving structures and between the micro and macro levels.

Different attempts have been made to apply complexity to economics, ranging from computational complexity to econophysics, connectivity complexity and bounded rationality complexity. Too often these attempts have missed the basic feature of economics that consists in the analysis of the role of the intentional, rent-seeking conduct in the interpretation of the behavior of agents. Agents are portrayed as automata that are not able to implement the intentional pursuit of their interest (Rosser, 1999 and 2004).

This Handbook presents a systematic attempt to show how building upon the achievements of complexity theory a substantial contribute to the economics of innovation can be implemented. At the same time it shows that an economic approach to complexity can be elaborated and fruitfully implemented. This chapter articulates the view that innovation is the emergent property of a system characterized by organized complexity. It implements an approach that enables to provide economic foundations to analyzing the incentives of economic action and the notion of organized complexity.

According to the theory of complexity, emergence is a phenomenon whereby well formulated aggregate behavior arises from localized individual behavior. Innovation can be seen as the combined result of the action of individual and heterogeneous agents with the structural characteristics of an organized system that is able to amplify and make consistent their action. The analysis of innovation as an emergent property of a system enables to combine the individualistic analysis of innovation as the result of intentional decision making of agents with the holistic understanding of the properties of the system into which such innovative action takes place and actually makes it possible.

Here complexity theory enables a major progress in the economic analysis of innovation, especially if the latter is defined as a productivity-enhancing event. It is difficult, in fact, to understand how and why economic agents would not push innovative activities to the point where their marginal costs match their marginal revenue. The appreciation of the special features of the system into which the individual action takes place and the specific processes by means of which the features of the system lead to the mergence of innovations marks an important analytical progress.

Economic of innovation may help the theory of complexity, and especially its applications to economic analysis, in two ways. First, complexity theory misses an economic analysis of the incentives and motivations of individual action. Economic agents are and remain rent-seeking individuals and it is necessary to understand why they may want to change and move the multidimensional spaces that characterized economic systems. Here the economics of innovation may contribute the analysis with the understanding of the out-of-equilibrium determinants of the attempt of agents to try and introduce innovations.

Second, in the complexity theory a major distinction is made between disorganized and organized complexity. In the former "the interactions of the local entities tend to smooth each other out" (Miller and Page, 2007:48). In the latter "interactions are not independent, feedback can enter the system. Feedback fundamentally alters the dynamics of a system. In a system with negative feedback, changes get quickly absorbed and the system gains stability. With positive feedback, changes get amplified leading to instability" (Miller and Page, 2007:50). Yet the theory of complexity does not provide an analysis of the endogenous determinants of the features of system. A basic question remains unresolved in much complexity thinking: how and when and why is a system characterized by organized or disorganized complexity??

It seems clear that all the effort made in the identification of innovation as an emergent property of a system as a mean to try and articulate its endogeneity would be spoiled if it eventually leads to accept the view that the organized complexity of a system is an exogenous and unpredictable characterization. Here the economics of innovation can provide important elements with its analysis of the endogenous formation of economic structures as the result of the recursive process of path dependent change.

Our attempt to implement the merging of the theory of complexity with the economics of innovation provides an alternative path to recent attempts to apply the methodologies elaborated by complexity into economics, such as complex networks (see Cowan, Jonard, Zimmermann, 2006 and 2007), percolation (see Silverberg and Verspagen, 2005), and NK-modeling (see Frenken, 2006 a and 2006b; Frenken and Nuvolari, 2004), for it focuses attention upon the scope of application of the basic tools of the economics of innovation to embrace the full range of analytical perspectives brought by the analysis of innovation as an emerging property stemming from the endogenous result of both the intentional, rent-seeking conduct of individual and heterogeneous agents and the endogenous characteristics of economic systems qualified by organized complexity.

This introductory chapter articulates an approach where agents retain the typical characteristics of economic actors, including intentional choice and strategic conduct, augmented by the attribution of potential creativity. In our approach economic agents may change both their production and their utility functions. The determinants and the effects of this potential creativity and the context into which it can be implemented, however, require careful investigation. The actual creativity of agents is not obvious and spontaneous.

To investigate the determinants of the actual creativity of agents to sequential steps are necessary. First, the incentives to change must be identified and qualified. Agents are reluctant to change their production and utility functions and a specific motivation is necessary to induce them to try and change their routines. Second, the he localized context of action and the web of knowledge interactions and externalities into which each agent is embedded is crucial to make their reaction actually creative, as opposed to adaptive, so as to shape the actual effects of their endogenous efforts to change their technologies and their preferences.

The analysis of the effects must include, next to the introduction of innovations that increase the efficiency of the production process, the structural consequences upon the context of action. The successful introduction of new localized technologies, in fact, changes the structure of the system and hence the flows of knowledge externalities and interactions. This dynamic loop exhibits the characters of a recursive, non-ergodic and path dependent historic process. This approach enables to move away from the static, low-level complexity- of general equilibrium that applies when both technologies and preferences are static, or the smooth and ubiquitous growth based upon learning processes and spontaneous spillover of the new growth theory. It makes it possible a significant progress also with respect to evolutionary thinking where the causal analysis of the determinants of the generation of innovations is reduced to the random walks of spontaneous variation.

This approach provides the tools to grasp the system dynamics of technological change as an endogenous and recurrent process that combines rent-seeking intentionality at the agent levels with the appreciation of the knowledge externalities and interactions that stem from the structural characters of the system.

2. THE ECONOMICS OF INNOVATION AS AN EMERGING PROPERTY OF AN ORGANIZED COMPLEXITY

Economics of innovation studies the determinants and the effects of the generation of new technological knowledge, the introduction of innovations in product, process, organization, mix of inputs and markets, their selection and eventual diffusion. Innovation takes place when it is able to engender an increase in output that exceeds its costs.

Technological and organizational changes are defined as innovations only if and when the two overlapping features of novelty and efficiency coincide. Changes are innovations if they consist at the same time in the introduction of a novelty that is also able to yield an increase in the relationship between inputs and outputs. Total factor productivity can be considered a reliable indicator of the relationship between inputs and outputs of the production processes: novelties that are actually able to increase the ratio of inputs to output are true innovations. Either characteristic is necessary to identify an innovation. Only if we retain such a strict definition of innovation, as a productivity-enhancing novelty can we grasp its out-of-equilibrium characteristics.

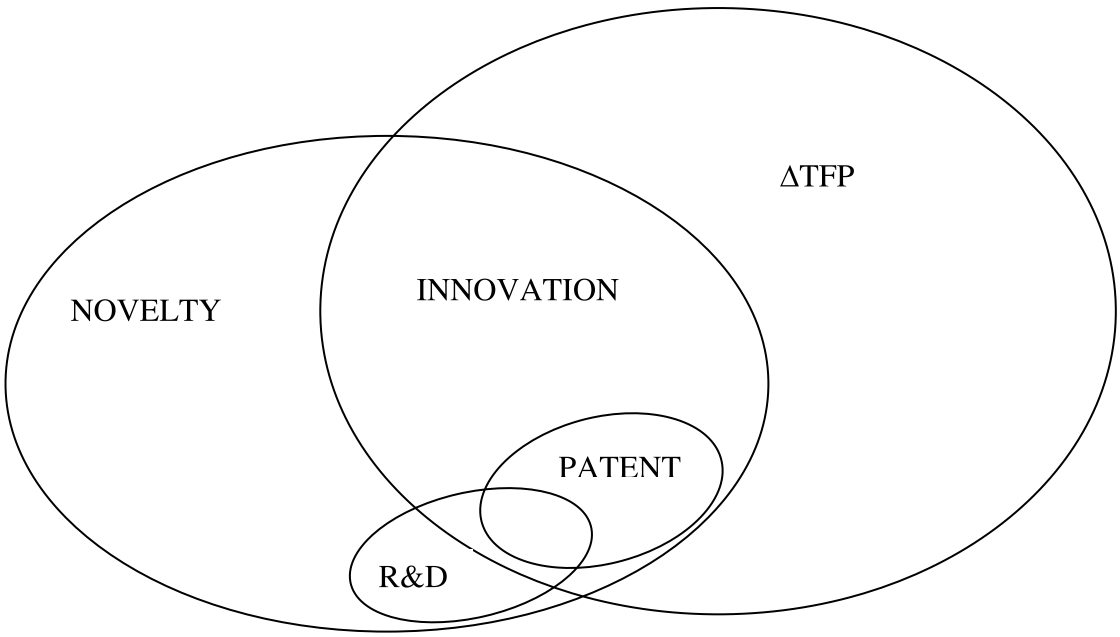
It is clear in fact, on the one hand, that indeed total factor productivity may increase for a variety of other factors, especially if and when markets are not in equilibrium. On the other however it is also clear that often novelties do not last and are selected out in the market selection process with no actual economic effect. On a similar ground we see that minor changes in products may feed monopolistic competition and do not increase the efficiency of the production process at large. It is not surprising that much theorizing upon the new theories of growth never tackles the issue and prefers a more comfortable definition of innovation as a form of increase in the variety of products.

Innovation is the result of a variety of activities. Learning processes of various kinds play a major role in the accumulation of the competence that is necessary to generate new technological knowledge and eventually to introduce innovations. Research and developments indicators are able to grasp only a fraction of such activities. Much R&D on the other hand is funded and performed to generate novelties that are not able to increase the efficiency of the production process. As it is well known only a fraction of the technological innovations being introduced is represented by patent statistics. Neither R&D nor patent statistics account for innovations in organization, input mix and markets. Total factor productivity indicators instead can grasp their economic effects. Hence total factor productivity indicators are likely to provide an accurate measure of the actual amount and extent of the innovations being introduced.

In sum, new products, new processes, new organization methods, new inputs and new markets can be defined as innovation only if they yield an increase in total factor productivity. Hence the marginal product of innovation efforts exceeds its marginal costs. This is at the origin of a serious problem for economics.

INSERT FIGURE 1 ABOUT HERE

INNOVATION: NOVELTY AND PRODUCTIVITY



Innovation is a productivity enhancing novelty

The merging of the theory of complexity and the economics of innovation provides a new way to integrate economic and complexity thinking and contributes to the building of an economic theory of complexity that puts the endogenous and systemic emergence of innovation at the core of the analysis. The continual introduction of new technologies and their selection is seen as the emerging and systemic property of an out-of-equilibrium dynamics characterized by path dependent non-ergodicity and interactions both among agents and between micro and macro levels. The organized complexity of the system that enables the emergence of innovations is itself the product of the recurrent and path dependent interaction of rent-seeking agents.

Technological and structural change is the result of a sequential process of systemic change where agents are never able to anticipate ex-ante the outcome of their reactions to emerging surprises. The changing characters of their localized context of action in fact engender out-of-equilibrium conditions to which they react. When knowledge externalities and interactions engender positive feedbacks their reaction is creative. Firms are able to change both their technologies and the structure of the system: a recursive, historic and path-dependent process of change takes place. When the context of action does not provide knowledge externalities and interactions sufficient to engender positive feedbacks, the reaction of firms is adaptive and a single static attractor consolidates: general equilibrium analysis applies.

In general equilibrium economics the preferences and the technologies, of the representative agent and hence her production and utility functions, are allowed to change only as the result of exogenous shocks. As soon as the notion of endogenous change is introduced and heterogeneous agents are credited with the capability to change their production and utility functions in response to economic stimulations, the general equilibrium analysis appears a simplistic, yet systemic approach. The assumption of the necessary gravitation and convergence towards a single equilibrium point cannot be retained because of the changing center of attraction.

An innovation economics approach to complexity thinking makes it possible to overcome the limitations of both general equilibrium economics and evolutionary analysis into a system dynamics approach. It builds upon the integration of the Classical and Schumpeterian analysis of innovation as a form of reaction, to the changing conditions of product and factor markets, with the Marshallian analysis of externalities. The system dynamics approach contrasts the general equilibrium analysis where economic agents are indeed embedded in a systemic analysis but are not supposed to be able to change purposely their technologies and their preferences (Metcalfe, 2008).

The Marshallian approach provides the basic frame for a systemic understanding of the behavior of heterogeneous agents that are interdependent within a dynamic context characterized by increasing returns and increasing levels of division of labor engendered by specialization.

The Marshallian approach to the economics of knowledge has provided the basic tools for the new growth theory. In the new growth theory knowledge stems from learning processes that are intrinsic to the economic activity. Following the Arrovian legacy, the new growth theory shares the view that knowledge is characterized by an array of idiosyncratic features such non-appropriability, non-divisibility, non-excludability, non-exhaustibility that are the cause of knowledge externalities and contribute the continual and homogeneous introduction of innovations (Arrow, 1962 and 1969). The new growth theory however has not been able to appreciate the endogenous, idiosyncratic and dynamic character of knowledge externalities. Assuming that knowledge externalities are given and evenly distributed in time and space, the new growth theory claims that technological change takes place without discontinuities and leads to smooth dynamic processes (Romer, 1994). These assumptions contrast sharply the rich evidence about the punctuated and discontinuous rates and directions of technological change (Mokyr, 1990a, 1990b, 2002)

The Marshallian approach to partial equilibrium analysis provides a rich analytical apparatus that emphasizes the idiosyncratic variety of agents and markets that interact in a systemic context characterized by endogenous structural change. The Marshallian notion of partial equilibrium, enables the use of the foundations of microeconomics as they provide the analytical context into which the maximizing conduct of individual agents can be interpreted and yet makes room for the understanding of the process of structural and technological change. The general equilibrium of the system however cannot be considered as the result of the integration of the different partial equilibrium contexts of analysis. Structural and technological change, with their intertwined characters of growth, development and change are necessary components of an aggregate dynamics that exhibits strong elements of contingent discontinuity as well as historic hystersis (Anderson, Arrow, Pines, 1988).

For these reasons the Marshallian approach can be retained and integrated with the Schumpeterian and classical approach that stresses the role of the creative reaction of firms caught in out-of-equilibrium conditions into an economics of complexity that emphasizes the endogenous emergence of technological change. The understanding of the dynamics of the system requires the grasping of the cause and determinants of the changing centers of gravitation of the system (Blume and Durlauf, 2005).

Evolutionary economics has much contributed to place innovation at the center stage of economic analysis. Evolutionary economics has built an outstanding corpus of knowledge about the characteristics of innovation and of technological knowledge with the identification of important taxonomies and significant sequences. Evolutionary economics however has focused much more the analysis of the selective diffusion of new technologies rather then the analysis of the actual determinants of the generation of new technological knowledge and the introduction of innovations (Foster, 2005). Consistently with the general evolutionary frame of analysis, innovation is regarded as the product of random variation, rather then the result of the intentional action of agents. The analysis of the determinants of technological change has been left at the margin of the exploration. This seems quite paradoxical. Evolutionary economics is not able to explain the determinants of the central mechanism of economic change.

In our approach, innovation is not only the result of the intentional action of each individual agent, but it is the endogenous product of dynamics of the system. The individual action and the system conditions are crucial and complementary ingredients to explain the emergence of innovations.

Innovation cannot be considered but the intentional result of the economic action of agents: it does not fall from heaven. Neither is it the result of random variation. Dedicated resources to knowledge governance are necessary to implement the competence accumulated by means of learning and to manage its exploitation. Agents succeed in their creative reactions when a number of contingent external conditions apply at the system level. Innovation is made possible by key systemic conditions: "innovation is a path dependent, collective process that takes place in a localized context, if, when and where a sufficient number of creative reactions are made in a coherent, complementary and consistent way. As such innovation is one of the key emergent properties of an economic system viewed as a dynamic complex system" (Antonelli, 2008:I).

The appreciation of the systemic conditions that shape and make innovations possible, together with their individual causes lead to the identification of innovation as an emergent property of a system. This approach provides a solution to the conundrum of an intentional economic action whose rewards are large than its costs, only if the organized complexity that enables the mergence of innovations is explained as an endogenous and dynamic process engendered by the interactions of rent-seeking agents.

TABLE 1. DEADS ENDS AND NEW PROSPECTS FOR THE ANALYSIS OF SYSTEMS WHERE INNOVATION IS AN ENDOGENOUS, TFP-ENHANCING PROCESS

	MICRO	MESO	MACRO
GENERAL EQUILIBRIUM	THE REPRESENTATIVE AGENT CANNOT INNOVATE	TRANSACTIONS	LOW-LEVEL STATIC COMPLEXITY
MARSHALLIAN PARTIAL EQUILIBRIUM	VARIETY	EXTERNALITIES	STRUCTURAL CHANGE
ARROVIAN LEGACY	LEARNING	KNOWLEDGE GOVERNANCE	DYNAMIC EQUILIBRIUM
DARWINIAN EVOLUTIONISM	RANDOM VARIATION	SELECTION, EMERGENCE OF DOMINANT DESIGNS	STRUCTURAL CHANGE (clusters, sectors, filieres)
COMPLEXITY	NO INTENTIONAL ACTION	INTERACTIONS NETWORKS	SYSTEM DYNAMICS
COMPLEXITY CUM INNOVATION	CREATIVE REACTION IS INTENTIONAL CUM GENERATIVE RELATIONS	NON-ERGODIC CHANGES IN ENDOWMENT AND NETWORK ARCHITECTURE	ORGANIZED COMPLEXITY

The rich frame of analysis elaborated by the economics of innovation can be integrated with the systemic foundations of general equilibrium economics and the dynamic analysis of evolutionary economics, This effort can contribute a complex system dynamics where technological change is the central engine of the evolving dynamics-viewed and it is the result of the creative response of intentional agents, embedded in an evolving architecture of market, social and knowledge interactions (Antonelli, 2007, 2008a and 2009a).

In such an approach, (synthesized in Table 1) innovation is an emergent property of the system that, as an organized complexity, qualifies and makes possible the creative response of agents. The innovation approach to economic complexity builds on a number of basic assumptions and tools of analysis:

A) From reactivity to creativity. Agents are reactive, i.e. agents can react to unexpected and unpredictable changes and change their production and utility functions, hence their technologies and preferences are endogenous. The characteristics of the local context into which agents are embedded play a crucial role to assess whether their reaction is adaptive or actually creative. In the latter case agents will simply move on the existing maps of isoquants and indifference curves. In the former, instead, agents can effectively change their location in the knowledge, technology and regional space, according to their own specific characteristics and the features of local endowments, including the network of transactions and interactions into which they are embedded.

B) Knowledge externalities and interactions. The amount of knowledge externalities and interactions available to each firm influences the actual possibility to make the reaction of firms adaptive as opposed to creative and able to introduce localized technological changes. Each agent has access only to local knowledge interactions and externalities, i.e. no agent knows what every other agent in the system at large knows. Location in a multidimensional space, in terms of distance among agents and their density, matters. Agents are localized within networks of transactions and interactions which are specific subsets of the broader array of interactions and transactions that take place in the system. Positive feedbacks take place when the external conditions into which each firm is localized, enable the creative reaction of each firm to engender the actual introduction of innovations and feed the introduction of further innovations by a larger number of agents so that technological change becomes a generalized and collective process.

C) Localized technological change. Agents are rooted in a well defined set of characteristics that stem from the quasi-irreversibility of their tangible and intangible inputs, including their location in the multidimensional space. At each point in time, however, agents can switch, i.e. change the structure of their inputs and their location, but only with the investment of dedicated resources. Specifically agents, at each point in time, can change, within a limited ray, their knowledge, their technology and the structure of their interactions. Technological change is inherently localized: each agent can innovate, but only in the surroundings of its original multidimensional location, in technical space, when positive feedbacks in regional and knowledge space are at work. Hence agents are heterogeneous. They are characterized by distinctive and specific characteristics concerning both their competence, the endowment of tangible and intangible inputs and their location in the space of interactions.

D) Recursive dynamics with endogenous structures. The outcome of the creative reaction of each agent and the likelihood of its innovative behavior is strictly dependent on the web of interactions that take place within the system. The introduction of localized technological changes depends upon the extent to which the creative reaction of firms caught in out-of-equilibrium conditions is implemented by the access to knowledge externalities and interactions. Hence at each point in time, the architectural topology of the system, i.e. the meso-characteristics and the structure of interactions of the agents in their relevant multidimensional spaces, plays a key role. The architecture of the system and the structure of interactions, however, is itself endogenous as it is the result of the localized action of agents. Agents can innovate as well as change their location in the multidimensional space, their communication channels, their systems of interactions and their location in the flows of transactions. The introduction of localized innovations changes the structure of the system and hence the amount of externalities. The new levels of externalities affect the new chances of introduction of localized technological changes. The recursive dynamics is set.

E) *Persistence and path-dependence*. When non-ergodicity applies, dynamic processes are characterized by persistence: a little shock at a particular point in time, affects the long-term dynamics of a system. Social and knowledge interactions among creative agents, as well as transactions in the market place, engender generative relations that enable agents to change locally their own production and utility functions. The localized action of agents both in terms of introduction of new technologies and changes in their location engenders phase transitions consisting in qualitative changes determined by small changes in the parameters of the system. As a consequence both technological knowledge and the architecture of the system are changed in a recursive and path dependent process.

In such a context innovation is an emergent property that takes place when a the complexity is organized, i.e. when a number of complementary conditions enable the creative reaction of agents and makes it possible to introduce innovations that actually increase their efficiency. The dynamics of complex systems is based upon the combination of the reactivity of agents, caught in out-of-equilibrium conditions, with the features of the system into which each agent is embedded in terms of externalities, interactions, positive feedbacks that enable the generation of localized technological change and lead to endogenous structural change. The process is characterized by path dependent non-ergodicity.

Let us now turn our attention to analyze the building blocks of our approach. The following chapters show how the use of the basic tools of the economics of innovation can implement a rigorous representation of the system dynamics of technological change where the basic intuitions of complexity theory are implemented and put at work.

3. CREATIVE AND ADAPTIVE REACTION

Consistently with the dominant view that technological change is exogenous or, at best, the automatic product of spontaneous learning procedures, very little attention has been paid to the analysis of the determinants of innovation. This contrasts the size and the wealth of the large literature that has explored the effects of innovation on profitability, growth, performance, industrial structures. Even evolutionary economics assumes that innovation is the spontaneous outcome of random mutations: agents introduce innovations randomly without any specific motivation. In evolutionary economics there is no attempt to identify the historic, regional and institutional determinants of the generation of innovations. Much effort is made, instead to, explore the features of the selection, adoption and diffusion mechanisms of the 'spontaneous' flow of innovations. The analysis of the determinants of the introduction of innovation remains substantially under-investigated.

The basic reference here is provided by the literature that has debated and implemented the so-called Schumpeterian Hypothesis on the relations between forms of competition and incentives to innovate. The consensus was reached about the argument that the rate of innovation is higher when forms of oligopolistic rivalry characterize the market structure. When perfect competition prevails, firms cannot bear the burden of research activities. When the number of competitors is too small, close to monopolistic conditions, incentives to innovate are missing. Cutthroat competition risks to reduce the incentives to introduce technologies for the intrinsic non-appropriability of knowledge and the high risks of imitation and entry of new competitors that can take advantage of opportunistic behavior. Some intermediary levels of workable competition, comprised between the extremes of monopoly and perfect competition, among large firms might favor the rate of introduction of innovations. Oligopolistic market structures and the large size of firms are viewed as positive factors able to sustain the rates of introduction of innovations (Scherer, 1967 and 1970; Dasgupta and Stiglitz, 1980; Fisher and Temin, 1973; Link, 1980).

In the classical economics of technological change two different frames have been identified to try and explain the endogenous determinants of the introduction of innovations: a) the inducement approach elaborated along the lines of the early contributions of Karl Marx, b) the demand pull approach elaborated by the Post-Keynesian school.

According to the first approach the condition of factor markets play a key role in inducing the introduction of innovations (Ruttan, 2001). Firms try and introduce technological change as a form of meta-substitution to save on the inputs that are relatively scarce (Samuelson, 1965) or whose cost is increasing (Hicks, 1932; Kennedy, 1964).

The second approach elaborates the view that technological change is pulled by the aggregate demand. Following the Post-Keynesian line of argument Smith-Young-Kaldor, the introduction of innovations should be the result of the increase in the division of labor and in the specialization that follows the increase in the demand.

Our approach impinges upon the late contribution of Joseph Schumpeter and focuses the role of the relations between profitability and innovation. The analysis of the causal relations between levels of profitability, as distinct from competition, enables to elaborate a consistent and coherent frame of analysis and integrate these different and yet complementary strands of literature that share the view that technological change is endogenous and that the decision to innovate is an intentional and relevant component of economic decision-making.

The contribution of the behavioral theories of the firm provides substantial help in this effort. The decision to innovate, in fact, cannot be treated with the standard maximization procedures. The outcomes of innovations are hard to predict, and the actual chances of introduction of successful innovations are subject to radical uncertainty. The introduction of innovations is the result of a complex sequence of intentional decision-making that takes place when firms are found in out-of-equilibrium conditions. According to James March (March and Simon, 1958; Cyert and March, 1963), firms are not profit maximizers. Firms are able to rely upon procedural, as opposed to substantive, rationality: firms use satisfying procedures and identify satisfactory levels of performances. Firms are risk adverse and hence reluctant to change their routines, their production processes, their networks of suppliers, their products and their marketing activities. Firms can overcome their intrinsic inertia and resistance to change only when unexpected changes in their environment push them to take the risks associated with innovation (March and Shapira, 1987).

The integration into a single frame, characterized by the analysis of profitability, of such elements enables to elaborate the hypothesis that firms try and innovate when they are found in out-of-equilibrium conditions, that is when profits are either below or above the norm. When equilibrium conditions prevail and there are no extraprofits, firms are not induced to try and change their technologies, neither their organizations, markets and input mixes. According to this approach a non-linear relationship between profits and innovation is at work.

a) The Marxian legacies

Marx contributed the first elements of the theory of induced technological change. The introduction of new capital-intensive technologies is the result of the intentional process of augmented labour substitution. When wages increase, capitalists are induced to introduce new technologies that are embodied in capital goods. Hence technological change is introduced with the twin aim of substituting capital to labor so as to reduce the pressure of unions and increasing the total efficiency of the production process (Marx, 1867).

John Hicks (1932) and Fellner (1961) extracted from the analysis of Karl Marx the basic elements of the theory of the induced technological change: firms are induced to change their technology when wages increase. Technological change is considered an augmented form of substitution: technological change complements technical change. Binswanger and Ruttan (1978) eventually articulated a more general theory of induced technological change: firms introduce new technologies in order to save on the production factors that are relatively more expensive. Such production factors can be labor, as much as energy or even capital in specific circumstances. The induced technological change approach has been criticized by Salter (1966) according to whom firms should be equally eager to introduce any kind of technological change, either labour- or capital-intensive, provided it enables the reduction of production costs and the increase of efficiency.

An important facet of the Marxian analysis is missing in the induced technological change approach. The analysis of the Marxian contribution by Rosenberg (1976) highlights the limitations of the induced technological change approach and helps to understand the key role of profitability. Firms try and contrast the decline in their profitability, stemming from the increase in wages, with the introduction of technological innovations. Starting from a common reference to Marx, Hicks paved the way to a tradition of analysis that focuses the role of the changes in the prices of production factors in inducing technological innovations. Rosenberg, instead, stresses the role of the decline in profitability as the focusing mechanism that pushes firm to undertake innovative activities. According to Rosenberg, firms innovate in order to restore the levels of profitability (that have been undermined by the raise in wages). According to Hicks firms react to the increase in wages (and the related decline in profitability). As Nathan Rosenberg (1969) argues Marx provides elements to build much a broader inducement hypothesis, one where the levels of profitability are a cause of endogenous technological change. This line of analysis has received much less attention in the economics of innovation, and yet it provides a clear replay to Salter's arguments

b) The role of profitability in the demand pull hypothesis

The post-keynesian approach elaborated by Kaldor (1972 and 1981) stressed the key role of the demand in the explanation of the endogenous origin of technological change. To do so Kaldor had revisited the dynamic engine put in place by Adam Smith. According to Adam Smith the division of labour is determined by the extent of the market and is the cause of the increase of specialization. This leads to the accumulation of new technological knowledge, and eventually to the introduction of technological innovations. Technological innovations in turn lead to an increase in productivity. The increase in productivity leads to an increase in the demand and hence of the extent of the market. According to Adam Smith the relationship between division of labor, specialization, increase of competence, introduction of technological innovations, productivity growth, increase in demand and new division of labor consists in a recursive loop. Building on this interpretation Kaldor argued that an increase in the levels of the aggregate demand would engender an increase in the division of labor, hence of specialization, and eventually of the rate of introduction of technological innovations. The so-called 'demand-pull' hypothesis was borne. Schmookler (1966) provided empirical support to the hypothesis that demand growth pulls the increase of technological knowledge, hence of inventions and eventually technological innovations. Rosenberg and Mowery (1979) provide an outstanding account of the pervasive role of the demand-pull hypothesis within the post-Keynesian approach.

Less attention has received a previous contribution by Schmookler (1954) according to which the increase in the demand leads to the generation of additional technological knowledge and the eventual introduction of technological innovations via the increase in the profitability of both inventors and innovators. Firms are pulled to generate new technological knowledge and to introduce technological innovations by the high levels of prices for the products that are the object of an increasing demand and by the high levels of rewards that are attached. Young scholars specialize in the fields were wages increase because of the demand for their competence. New firms enter with innovative ideas in the industries where profits are growing because of the increase of the demand. Incumbent firms are induced to innovate by the growth in the demand and the extraprofits that are attached.

Following this line of analysis we can claim that excess demand engenders out-of-equilibrium conditions that lead to an increase in prices and in profitability. Out-of-equilibrium conditions here are determined by the un-expected increase in the demand: had the firm anticipated the high levels of the demand, current supply would have already accommodated it with no increase in prices and hence in profits. When the demand fetches un-expected levels, instead, prices increase and consequently profits. Then firms are pulled to accommodate the increased levels of the demand with an increase in supply. The increase in supply however can be obtained both via investments with a given technology and an increase in productivity of the given resources, via the introduction of technological innovations. The accumulation of competence and expertise based upon learning processes enables the generation of new technological knowledge. Extraprofits provide the opportunity to fund the generation of new technological knowledge and the introduction of technological innovations. Hence the increase in demand feeds the introduction of innovations by means of an increase of profits above the norm. In other words we can easily reconcile the demand-pull hypothesis with the argument that extra profits favor the introduction of additional innovations.

The chain-loop elaborated by Kaldor after Smith can be integrated with a an additional ring: increase in demand, extraprofits, new division of labor, specialization, increase of competence, introduction of technological innovations, productivity growth (Scherer, 1982).

The increase in demand engenders an increase in profits that in turn provides both the incentives and the opportunities for the introduction of innovations. The incentives are the determined by the perspective to take advantage of the excess demand via the increase in supply by means of new productivity-enhancing technologies. The opportunities stem from the resources made available by extraprofits.

c) The Schumpeterian legacies

The Neo-Schumpeterian school has been very selective in implementing the Schumpeterian approach and has neglected some crucial aspects of the Schumpeterian legacy. As a matter of fact the scope of the analysis elaborated by Schumpeter provides ammunitions to elaborate a radical departure from equilibrium analysis.

With the analysis of the role of creative reaction, Schumpeter (1947) fully elaborates the view that firms and agents at large are not passive adapters but can react to the changing conditions of both product and factor markets in a creative way, with the introduction of innovations, both in technologies and organizations and changing their products and processes. If firms are credited with the capability to innovate as a part of their business conduct, the notion of creative reaction becomes relevant. The conditions that qualify it warrant systematic investigation.

Schumpeter (1947) makes the point very clear: "What has not been adequately appreciated among theorists is the distinction between different kinds of reaction to changes in 'condition'. Whenever an economy or a sector of an economy adapts itself to a change in its data in the way that traditional theory describes, whenever, that is, an economy reacts to an increase in population by simply adding the new brains and hands to the working force in the existing employment, or an industry reacts to a protective duty by the expansion within its existing practice, we may speak of the development as an *adaptive response*. And whenever the economy or an industry or some firms in an industry do something else, something that is outside of the range of existing practice, we may speak of *creative response*. Creative response has at least three essential characteristics. First, from the standpoint of the observer who is in full possession of all relevant facts, it can always be understood *ex post*; but it can be practically never be understood *ex ante*; that is to say, it cannot be predicted by applying the ordinary rules of inference from the pre-existing facts. This is why the 'how' in what has been called the 'mechanisms' must be investigated in each case. Secondly, creative response shapes the whole course of subsequent events and their 'long-run' outcome. It is not true that both types of responses dominate only what the economist loves to call 'transitions', leaving the ultimate outcome to be determined by the initial data. Creative response changes social and economic situations for good, or, to put it differently, it creates situations from which there is no bridge to those situations that might have emerged in the absence. This is why creative response is an essential element in the historical process; no deterministic credo avails against this. Thirdly, creative response –the frequency of its occurrence in a group, its intensity and success or failure- has obviously something, be that much or little, to do (a) with quality of the personnel available in a society, (b) with relative quality of personnel, that is, with quality available to a particular field of activity relative to the quality available, at the same time, to others, and (c) with individual decisions, actions, and patterns of behavior." (Schumpeter, 1947:149-150).

Schumpeter makes a sharp distinction between adaptive and creative responses. Adaptive responses consist in standard price/quantity adjustments that are comprised within the range of existing practices. Creative responses are triggered by strategic interactions. The rivalry among firms able to introduce –purposely- new technologies is a major factor in fostering the rate of technological change (Scherer, 1967). Here, interactions take place in the market: the extent to which firms innovate is stirred by the change in behavior of other competing agents, namely the introduction of innovations, by neighbors in the product and output markets.

Creative responses consist in innovative changes that can be rarely understood *ex ante*, shape the whole course of subsequent events and their 'long-run' outcome: their frequency, intensity and success is influenced by a variety of conditional factors that are both internal to each firm and external. For a given shock, firms can switch from an adaptive response to a creative response according to the quality of their internal learning processes, and the context into which they are embedded. Learning in fact is a necessary but not sufficient condition for the generation of new knowledge. The notion of creative response elaborated by Schumpeter can be considered the synthesis of a long process of elaboration.

One extreme can be identified in *Business Cycles* (1939). Here the appreciation of the role of creative reaction in economic history, is fully consistent with the Rosenberg-Marx line of analysis. Here Schumpeter suggests that the gales of innovations peak in the periods of decline of the rates of profitability and growth. After a sustained phase of expansion, the decline in the opportunities for further growth of output and profits induces firms to innovate. Hence the business cycle and the innovation cycle are specular. In periods of expansion the rates of introduction of innovations decline. When profitability and growth are high, firms exploit and refine the technological innovations introduced in the periods of crisis. Technological change is characterized by the introduction of minor and incremental innovations. On the opposite, major breakthroughs take place when the search for new technologies acquires a strong collective character. When the rates of growth are lower, and the profitability declines, in fact, many firms try and react by means of the systematic search for new ideas. The generalized decline in profitability and the complementarity among individual search activities stemming from the intrinsic indivisibility of knowledge and favors the emergence of collective knowledge pools and hence the chances of introduction of radical innovations. The causal relationship between profitability and innovation acquires in *Business Cycle* an aggregate dimension.

In *Capitalism socialism and democracy* (1942), Schumpeter identifies the large corporation as the driving institution for the introduction of innovations. The corporation is itself an institutional innovation that favors the introduction of technological innovations for many reasons. As a large literature has stressed, the corporation can use the barriers to entry as a barrier to imitation. The risks of uncontrolled leakage of proprietary knowledge in fact are reduced when the innovator enjoys the benefits of

economies of scale and absolute cost advantages so that new competitors might imitate but cannot actually enter the market place.
Schumpeter is very clear in stressing the role of the corporation as a superior allocation and selection mechanism that reduces the inefficiency of financial markets in the provision of funds to innovative undertakings and increase the matching between competence and resources available to develop new technologies. Schumpeter regards the corporation as a hierarchical system that makes it possible the coordinated working of internal markets where financial resources matched with competence can be fueled towards risky but innovative undertakings (Schumpeter, 1947).

Within the corporation the resources extracted by the extra-profits match the competences of skilled managers and the vision of potential entrepreneurs. The Schumpeterian corporation can reduce the intrinsic failure of competitive markets in the allocation of resources to research, in the identification of the proper level of rewards and hence incentives to the introduction of innovations. The corporation is an effective institution able to substitute the financial markets in the provision and allocation of funds to innovative activities because it combines financial resources and learning with entrepreneurial vision within competent hierarchies, provided that extra-profits can be earned and a consistent share is directed towards the generation and introduction of innovations (Penrose 1959).

It seems clear that the careful reading of the full range of contributions of Schumpeter suggests that firms try and innovate both when their profits fall below satisfying levels and when profitability provide the resources to use systematically innovation as a competitive tool. Here it is clear that the higher are the profits and the larger the opportunities to use a share to fund research activities and hence to increase the rates of introduction of new technologies.

Profitability and innovation: The hypothesis of a U-shaped relationship

The appreciation of the Schumpeterian notion of creative response and the identification of out-of-equilibrium conditions in: a) the reappraisal of the Marxian analysis of the role of the decline in profitability in pushing firms to innovate as a key component of the augmented induced technological change approach, b) the failure-induced approach elaborated by Schumpeter in Business Cycles, c) the reconsideration of the Schumpeterian analysis of the extra-profits associated with the corporation as an institutional engine for continual introduction of innovations, d) the appreciation of the role of extra-profits in providing incentives and opportunities to firms to innovate in the demand pull hypothesis; provides the basic tools to articulate the hypothesis of a causal relationship between profits above and below the norm, interpreted as indicators of out-of-equilibrium conditions, and innovation.

Profitability stirs the Schumpeterian creative response of firms. Firms are pushed to try and innovate and hence to search for new products and processes by the combined effects of incentives and opportunities that emerge when out-of-equilibrium conditions prevail. The levels of profitability are a clear and non-ambiguous indicator of the proximity to equilibrium conditions. While normal profits signal that the system is in equilibrium, both profits below and above the norm signal that the firm is away from equilibrium conditions. The larger is the variance of the levels of profitability and the stronger the conditions of out-of-equilibrium at the system level. The larger is the difference between the specific profit levels of each firm and the normal profitability and farther away are the local conditions from equilibrium.

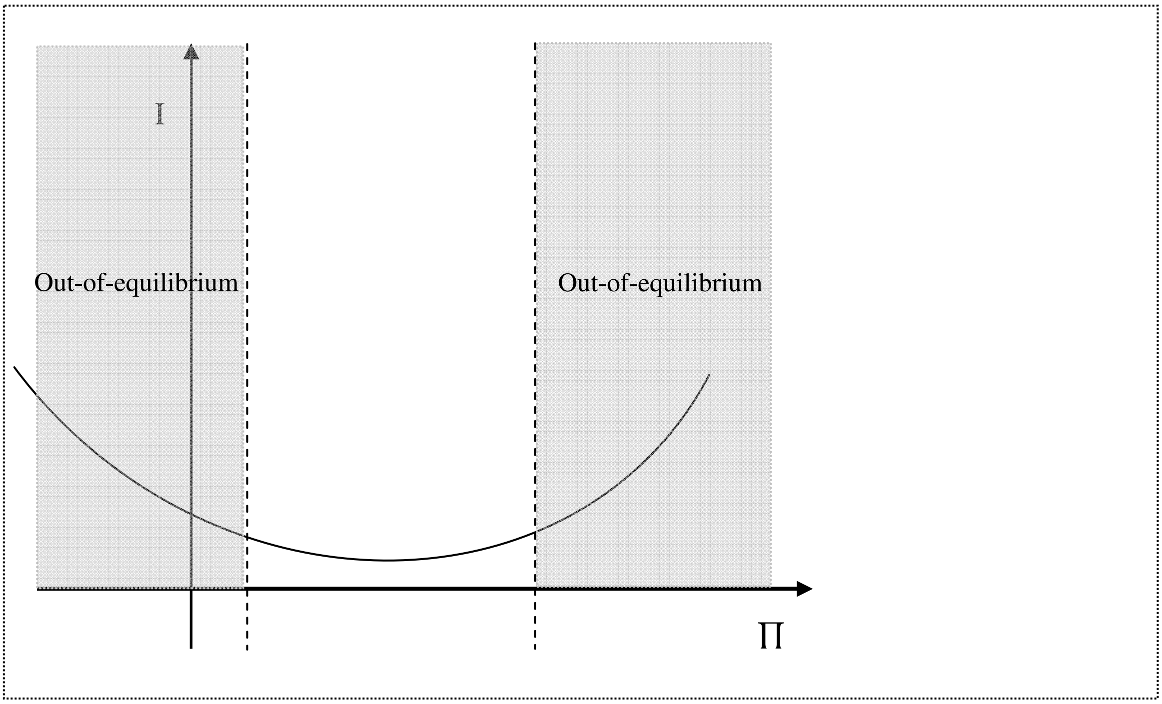
When the profits are below the norm and actually fetch negative values in absolute terms, firms understand that their survival is at stake. The low levels of profitability engender risks of survival that push firms to try and innovate. The intentional and explicit generation of new technological and organizational knowledge becomes necessary. To do so firms are induced towards an array of new routines such as the funding of research and development activities, the valorization of the tacit knowledge acquired by means of learning processes, the exploitation of external sources of new technological knowledge, the adoption and creative adaptations of new production processes and new products.

At the other extreme it is clear that the increase in demand engenders high levels of profits that provide firms with the incentives and the opportunity to introduce innovations. The resistance to change is much lower when organizations are performing and the abundance of resources makes it possible to identify the perspectives for new profitable ventures. Here change is intrinsically intertwined with growth and development, hence with new opportunities of upgrading for the members of the organization and for decision-makers. In product markets where workable competition prevails, and monopoly can be excluded, high profits signal conditions out-of-equilibrium associated with unexpected changes in either product or factor markets that enable firms to gain extra-profits, at least in the short term. Firms with high levels of profits are often characterized by dynamic capabilities and flexible organizations that have already being able to generate new technological knowledge and to introduce technological innovations (March and Simon, 1958; Penrose, 1959).

When profits are in the norm, firms have neither the incentives nor the opportunity to try and innovate. Internal resources to finance research and development and the eventual introduction of new prototypes are missing. At the same time inertia and resistance to change are not questioned, as managers do not feel the need to change the current state of their activities. The opportunity costs of risky undertakings whose failure might compromise the equilibrium of the company are very high. Product and factor markets should be close to condition of perfect competition: hence firms have little opportunities to exploit their innovations. Knowledge can hardly be appropriated and imitators can benefit of the knowledge generated by third parties. Credit rationing limits the access to financial resources that are necessary to generate new technological knowledge and to introduce technological innovations (Fazzari and Petersen, 1993; Bloch, 2005).

Assuming that workable competition characterizes the market place, and no monopolistic conditions can be identified, the causal relationship between profitability and innovation can be specified by a quadratic function: with low profits, below the average, including losses, firms have a strong incentive to innovate; with high profits above the norm, firms have important opportunities to fund research activities and hence innovate; firms with normal profits miss both incentives and opportunities. The basic argument is that combination of incentives and opportunities provides the basic mix of determinants to innovate. In the first case a failure inducement mechanism is at work: firms are induced to try and change their technologies and their organization when profits fall below a minimum threshold and their survival is put at risk. In the second case, incentives are lower but the opportunities for firms that enjoy extra-profits are strong. Firms can fund risky activities with a share of extra-profits and hence overcome the severe rationing of financial markets in the provision of resources for undertaking innovative activities. Firms with extra-profits moreover can guide internal markets by means of competent hierarchies so as to match financial resources, competence and innovative ideas. Firms with normal profits have both lesser incentives and opportunities to innovate.

FIGURE 2. THE QUADRATIC RELATIONSHIP BETWEEN PROFITS AND INNOVATION



Source: Antonelli and Scellato, 2009

The relationship between profit and innovation is shaped in Figure 2 where we set forth the basic argument that the rates of innovation are likely to be higher the farther away firms are from equilibrium conditions. The grey regions identify the conditions of out-of-equibrium, as measured by the levels of profitability with respect to average values, where profitability is below and above the average.

With low profits, fetching negative values, firms have a strong failure-induced incentive to innovate. Their survival is at risk. All the resources need to be mobilized in order to change the current state of activities, stop losses and introduce technological and organizational innovations that make it possible to increase their total factor productivity and hence to restore their competitivity.

Firms with profits in the average have no incentives and no opportunities to innovate. Rational decision-making inhibits the assumption of actions in domains that are characterized by radical uncertainty such as innovative undertakings, for the well-known problems of unpredictability both in their generation and exploitation.

Finally when firms enjoy extra-profits, at levels that are above the normal profitability, managers have the opportunity to fund research and innovative activities with their own internal funds. After payments of hefty dividends, managers can retain sufficient funds to undertake innovative projects designed to stretch the duration of market power. Extra-profits provide the opportunity to fund innovative activities and signal the existence of barriers to entry that increase de-facto the chances of appropriability of the stream of benefits stemming from the introduction of successful innovations.

In out-of-equilibrium the rent-seeking intentionality of agents overcomes their inertia and reluctance to try and innovate. Clearly our hypothesis is complementary to the so-called Schumpeterian Hypothesis about the relations between competition and innovation. It is clear in fact that when high profitability is associated with monopolistic conditions, firms have no incentives to try and innovate; when low profits are associated with cutthroat competition firms have not the possibility to try and innovate[1]. At the same time, however, our argument actually extends and qualify the Schumpeterian Hypothesis because oligopolistic rivalry and workable competition are indeed likely to stir the creative response of firms, and hence to push firms to try and innovate, but only when profits are either below or above the norm.

Antonelli and Scellato (2008b) have tested the hypothesis of a U-relationship between levels of profitability and innovative activity, as measured by the rates of increase of total factor productivity, on the evidence of a large sample of 7000 Italian firms in the years 1996-2005. The results are robust to different approaches to evaluate productivity growth rates and confirm that a strong causal relation holds between the quadratic specification of profitability and the growth rates of total factor productivity.

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[1] The so-called Schumpeterian hypothesis recently received new attention in the context of the new growth theory. This new literature has investigated the relationship between competition and innovation with contrasting results. Aghion and Howitt (1992) at first confirmed the Schumpeterian hypothesis according to which there is a negative correlation between competition and innovation, as measured by the intensity of R&D efforts. Subsequently Aghion and Howitt (1999), however, changed their mind and elaborated the view that competition should push firms to innovate. Finally Aghion et al. (2004) elaborated a compromise, suggesting that an inverted U shaped relation between competition and R&D expenditures might apply. The original findings of Scherer (1967) and Dasgupta and Stiglitz (1980) were confirmed after a long debate.

4. KNOWLEDGE EXTERNALITIES, INTERACTIONS AND POSITIVE FEEDBACKS

The analysis of knowledge as both an input and an output and the appreciation of knowledge non-appropriability and indivisibility as a source of knowledge for the generation of new knowledge have called the attention on the role of externalities (Antonelli, 2008).

The knowledge external to the firm, at each point in time, is as necessary and relevant complement to knowledge internal to the firm, in order to generate new knowledge. The access conditions to external knowledge are a key conditional factor in assessing the chances of generation of new knowledge. The generation of new knowledge is the specific outcome of an intentional conduct and requires four distinct and specific activities: internal learning, formal research and development activities, and the acquisition of external tacit and codified knowledge. Each of them is indispensable. Firms that have no access to external knowledge and cannot take advantage of essential complementary knowledge inputs can generate very little, if no new knowledge at all, even if internal learning combined with research and development activities, provides major contributions. Also the opposite is true. Firms that do not perform any knowledge generating activity but have access to rich knowledge commons can generate no new knowledge (Cohen and Levinthal, 1989)

In order to generate new knowledge, firms need to combine internal sources of knowledge such as intramuros research and development activities and learning processes with the systematic use of external knowledge as a primary input for the general production of new knowledge. No firm, in fact, can innovate in isolation. External knowledge is an essential input into the generation of new knowledge. External knowledge can substitute internal sources of knowledge only to a limited extent: full-fledged substitutability between internal and external knowledge cannot apply. Unconstrained complementarity however also appears inappropriate. Building on the large empirical evidence about the role of external knowledge, the hypothesis of a constrained multiplicative relationship can be articulated. External and internal knowledge, both in their tacit and codified form, are complementary inputs where none is disposable. The ratio of internal to external knowledge however seems relevant. Neither can firms generate new knowledge relying only on external or internal knowledge as the single input. With an appropriate ratio of internal to external knowledge instead internal knowledge and external knowledge inputs enter into a constrained multiplicative production function. Both below and above the threshold of the appropriate combination of the complementary inputs the firm cannot achieve the maximum output (Patrucco, 2008).

The appreciation of the effects of the non-appropriability of knowledge in terms of knowledge spillovers has lead to a renewed interest in the Marshallian notion of externalities. In the Marshallian tradition the notion of externalities has been rooted on the supply side for quite a long time and provides an interesting device to accommodate the evidence of increasing returns without destroying the basic foundations of standard microeconomics. Since the early Marshallian identification, externalities have received considerable attention. As a consequence many different kinds of externalities have been identified according to the specific characteristics of the external effects and the processes by means of which they take place.

The analysis of the role of the non-divisibility of knowledge in its generation has made it possible to identify three distinct characteristics of knowledge: knowledge cumulability, knowledge compositeness and knowledge fungibility. Knowledge cumulability takes place when new knowledge is the result of the diachronic complementarity of different vintages of knowledge. When knowledge is composite, new knowledge is generated by the recombination of bits of knowledge that belong to a variety of different fields. Finally, fungibility defines the downstream complementarity of any bit of knowledge. The same core of technological knowledge and competence can be applied to the production of a wide range of new fields.

This variety of knowledge has important implications for the analysis of knowledge externalities: each of them in fact highlights and stresses a facet of the complex architecture of relations, ranging from transactions to interactions, that matters. The study of externalities and specifically of knowledge externalities enables to grasp the relevance of the structural architecture of the system.

Externalities owe their name to the Marshallian analysis of the causal role of factors external –as opposite to internal factors- to the firm, in the explanation of increasing returns. Externalities indeed account for factor that are external to the each firm, but by no means are they external to the system. On the opposite they are the result of the emergence and possibly decline of the idiosyncratic characteristics of the system into which firms are embedded and that the action of firms consisting both in market strategies and in the introduction of innovations has generated. The analysis of knowledge externalities provides a clue to grasping their endogenous and dynamic character (David, Foray, Dalle, 1995).

Knowledge externalities

The notion of knowledge externalities has been operationalized by Zvi Griliches (1979) to provide an analytical context into which to wide gap between the private and social returns of R&D expenditures could be explained. Because of low appropriability firms fund R&D activities but can appropriate only a fraction of the total benefits. Other firms however can take advantage of the knowledge spilling in the atmosphere.

The notion of knowledge externalities captures the effects of the spontaneous availability of production factors at no costs within a given production function (Meade, 1952). Knowledge externalities do not require any interaction between the producers and the recipients of the external effects: they can be considered a characteristic of the 'atmosphere' of the districts into which firms are based. Knowledge externalities do not affect the production function: it remains exactly the same: some of the inputs are accessible at no cost: hence knowledge externalities affect only the cost equation. For the same token knowledge externalities do not affect the revenue function: the prices of the output generated by means of inputs acquired at a vantage because of externalities are not taken into account.

It seems more and more evident that the new growth theory impinges upon and elaborates the notion of knowledge externalities initiated by Griliches (1979). The new growth theory in fact has enriched and articulated the hypothesis that knowledge is a production factor spilling in the atmosphere of industrial districts. In this perspective the distinction between specific and generic knowledge is crucial. While specific knowledge is embedded in organizations and can be successfully appropriated by 'inventors'; generic knowledge is expected to spill freely in the atmosphere, with no costs for perspective users neither to acquire nor to use it. External knowledge can be accessed with no, search, transaction, interaction and communication costs (Romer, 1989 and 1994).

The investigation upon the flows of knowledge externalities has made it possible to appreciate important qualification about the characteristics of both the localized context into which knowledge externalities are found and the knowledge being disseminated.

The distinction between inter-industrial and intra-industrial externalities, also known as Jacobs externalities has paid a pivotal role in the analysis of the flows of external knowledge (Jacobs, 1969). The latter stress the complementarity of firms active within the same industry. The former identifies the complementarity of firms across industries. The empirical evidence confirms that flows of external knowledge take place among firms both within and between industries. When knowledge cumulability matters firms participate to implementing a common knowledge base and each can profit from the advances of the other members of the same industry. Intra-industrial flows of knowledge are more relevant when knowledge compositeness and fungibility matter. The former applies when vertical flows of knowledge across many industrial filieres are relevant for the knowledge generation in a single downstream industry. The latter takes place when the knowledge of a single industry upstream has a wide scope of application across a wide variety of industrial activities such as in the case of general purpose technologies are at work. It is clear that the industrial structure of an economic system here plays a key role in assessing the actual flows of knowledge externalities: holes and weaknesses in the vertical and horizontal mix of industries can play a critical role in the provision of knowledge externalities

A second distinction qualifies the context into which externalities take place. Externalities are local when their effects are circumscribed within a limited ray of action: proximity matters. Proximity in geographical space favors the dissemination of knowledge spillovers and reduces absorption costs. Distance has strong negative effects upon the density, reliability, symmetry, recurrence and quality of knowledge externalities (Boschma, 2005; Breschi and Lissoni, 2003). Externalities are global when external effects are relevant upon a wide space. In the former case proximity clearly matters. The identification of the relevant space however is not obvious: proximity in knowledge space may matter rather than in geographical one. The distinction between global and local externalities plays a major role as it calls attention upon the role of users and recipients. Perspective users of externalities are not just passive recipients: a proactive attitude is necessary to take advantage of externalities. Perspective recipients must act in order to benefit from externalities: mobility in space may be determined by the search for the access to externalities. The creation of communication channels may stretch the limitations of local externalities and provide the opportunity to remote recipients to take advantage of them. The analysis of the actions on the side of the perspective users of externalities provides a direct link to understanding the role of interactions as a step in a continuum of external effects.

TABLE 2. MAIN EFFECTS OF THE MATCHING BETWEEN TYPES OF EXTERNALITIES AND TYPES OF KNOWLEDGE

TYPES OF EXTERNALITIES/ TYPES OF KNOWLEDGE	CUMULATIVE KNOWLEDGE	COMPOSITE KNOWLEDGE	FUNGIBLE KNOWLEDGE
JACOBS	URBAN AGGLOMERATION	METROPOLITAN AGGLOMERATION	METROPOLITAN AGGLOMERATION
MAR	LOCAL POOLS OF KNOWLEDGE	UPSTREAM LINKS	DOWSTREAM LINKS
LOCAL	LOWER COMMUNICATION COSTS	IMPROVE GOVERNANCE MECHANISMS	INPROVE GOVERNANCE MECHANISMS
GLOBAL	FAVORS SCIENTIFIC COMMUNITIES	ENHANCES VARIETY OF SOURCES	ENHANCES VARIETY OF APPLICATIONS
TECHNOLOGICAL	DISTRICTS	NETWORKS	PLATFORMS
NETWORK	INCREASING RETURNS IN ADOPTION AND USE	INCREASING RETURNS IN ADOPTION AND USE	INCREASING RETURNS IN ADOPTION AND USE

Externalities are found both on the demand and on the supply side. Supply side externalities have received much more attention than externalities on the demand side. Externalities on the demand side consist in the effects of the identity and number of customers upon the choices of new consumers and users. The reputation of some users may exert a strong effect upon the choice of new customers. The preferences of customers become endogenous because of imitation effects. This is also the case when the quantity of customers matters. When the number of previous customers matters, network externalities are at work.

Network externalities apply on the supply side as well: the larger is the number of users of new information and communications systems, for instance, and the larger the output elasticity of digital equipment for the positive effects in terms of interaction and communication flows. Network externalities are a typical example of how the number of users of a given product may affect its utility (and output) elasticity.

Network externalities on the demand side have a strong effect on the adoption of new goods. The larger is the number of users and the lower are the adoption costs in terms of all the activities that are necessary to screening and assessing the functionality of new products.

The study of network externalities has brought to the identification of one additional and critical distinction between externalities that affect the costs function and externalities that affect the production (and utility) function. In the former case the structure of the preferences of consumers and the technology of firms are not affected by external factors. In the latter external conditions have a direct bearing upon the utility and production functions. The notion of interactions is often used in this context: because of increased opportunities to interact the form of the production function changes.

From social interaction to knowledge interactions

The study of interactions is a growing field of economics and more specifically of the economics of complexity. According to an extensive literature, interactions occur when the gains of undertaking an action to one agent are increasing with the number of other agents that undertake the same action. Interactions are a fundamental ingredient of complex dynamics. According to David Lane, complex economic dynamics takes place when the propensity to undertake specific actions of a set of heterogeneous agents change because of their interactions with one another within structured networks.

Interactions can be considered as different layers of a general mechanism of dynamic complementarity among the components of the system. Interactions include transactions as well as an array of other forms of relations among agents. When agents are credited with no capability to change endogenously their production and utility functions, transactions are the most important, if not the single form of interaction that economics study. When instead agents are credited with the capability to change their production and utility functions the relevance of other forms of relations, beyond transactions become relevant. So far interactions can be considered an extension and an analytical expansion of the traditional notion of externalities. The notion of interaction enables to grasp the endogenous and dynamic character of externalities.

Interactions are a specific form of interdependence whereby the changes in the behavior of other agents directly and explicitly affect the structure of the utility functions for households and of the production functions for producers (Durlauf, 2005). As Glaeser and Scheinkman state:” Each person’s actions change not only because of the direct change in fundamentals, but also because of the change in behavior of their neighbors” (Glaeser and Scheinkman, 2000:1).

The relations among agents in the economic system do not take place only in the markets and do not coincide only with market transactions, although of course they include market transactions. Transactions occur in the market place and are impersonal, punctual as opposed to recurrent, and individual. Other forms of relationship do take place. The notion of transaction does not apply within organizations where relations are recurrent and personal. The notion of transaction is not sufficient to exhaust the scope of action of a variety of relations that take place within markets when the exchanges of goods are mediated by personal contacts and are recurrent. When interactions matter, the conduct of an agent may affect the conduct of other agents without actual transactions among the parties. In such circumstances the notion of interaction applies and prices are no longer the single vectors of all the relevant information for decision-makers.

Interactions have important effects on the behavior of agents, especially when we assume that the structure of the preferences of agents on the demand side and the structure of technological knowledge of producers is exposed to mutual influence.

Models of interactions have been used to analyze a variety of empirical contexts ranging from unemployment, from stock market crashes to crime, from the endogenous change of preferences to the generation of new technological knowledge. The correlated actions among interacting agents induce amplified responses to shocks. Interaction multipliers are the result of positive feedbacks.

Different levels of interactions can be identified. A distinction between market, social and knowledge interactions can be made.

Market interactions consist mainly of transactions in product and factor markets. All changes in the price and quantities supplied and/or demanded by each agent, with given technologies and given preferences, have important effects on the conduct of each other agent. Market interactions consist of standard price/quantity adjustments. In the market place interacting, adaptive agents change their behavior but do not change the structure of their utility and production functions. As it is well known, in standard walrasian economics all changes in utility and production functions are exogenous, as they do not stem from economic decision-making. Microeconomics provides a superb analysis of the working of market interactions. With given preferences and given technologies the ripple of changes that follow the perturbations triggered by single changes eventually converge towards a stable and single attractor, often called general equilibrium.

Guiso and Schiavardi (2007) have provided an interesting test of the role of market interaction when firms can change their production functions. The baseline assumption of their analysis is that social interactions affect the behaviour of firms, as distinct from their performances. Specifically they test the hypothesis that the changes in employment of firms that are co-localized within industrial districts are shaped by significant social multipliers. Antonelli (1999) has applied the notion of network externalities to explore the effects of the size of computer networks on the output elasticity of digital capital.

Social interactions consist in the effects of the changes brought about by single agents upon the structure of preferences of other agents: the consequences on the demand side are most important. On the demand side social interactions have been analyzed to study the context into which the utility that an agent draws from an action is linked to the choices made by other agents within its reference group. When social interactions are at work and the structure of the preferences of each household is affected by the changes in the behavior of other agents: a social multiplier can be identified.

Intentional advertising campaigns master minded by firms may influence the preferences of consumers. Gregarious decision-making may lead to herd behavior. Herd behavior may imply that small differences in the timing of introduction of new products may have long lasting consequences. The notion of network externalities has been elaborated to model the changes in the utility of telecommunication services engendered by the changes in the size of telecommunication networks.

Social interactions may take place within organizations: they play a central role in changing the conduct of agents, their performances and their competence. Such interactions have no overlapping with any form of transactions: transactions do not occur within organizations and yet agents do interact extensively. Interactions are mediated and structured by the structure of the organization. The type of hierarchy and the architecture of communication channels affect and shape the density and recurrence of social interactions. Organizations differ with respect to the ability to detect and guide social interactions that take place within their borders.

As a matter of fact social interaction had been widely used in the economics of innovation. The epidemic tradition of analysis of the diffusion of innovations, initiated by Zvi Griliches (1957) is based upon the notion of social interactions defined as contagion. In the epidemic tradition contagion takes place by means of interactions and it is considered as a mechanism of dissemination of information. Potential users become aware of new goods and of their superior characteristics, with respect to existing goods, by means of social interactions. Social interactions spread information about the new goods and convince reluctant adopters about the advantages. The reputation of lead users may add on the informational effects and provide incremental incentives to potential users to actually adopt the new goods. Late adopters can be considered as rational users that save on information and search costs.

Recent advances in the analysis of diffusion processes have stressed the role of the structure of interactions. When the probability of interaction in the population of potential users, one of the key parameters of the logistic equation that is at the heart of by the epidemic approach, is assumed to have a Pareto distribution, as opposed to a normal one, it is sufficient that a few lead adopters have a large number of social interactions to spread the epidemic contagion to a large number of potential users so as to accelerate the speed of the process that is no loner bound to follow a S-shaped process. The analysis of the working of Internet networks has in fact provided large evidence about the key role of the hubs within scale-free networks that support o very large number of connections and enable information to reach instantaneously a wide range of connected users. The analysis of scale-free networks shows how important is the structure of social interaction to grasp their role in the dissemination of information (Barabàsi and Albert, 1999).

Quite a specific category of interactions leading to the actual introduction of new superior technologies is detected when we assume that firms do more than adjusting prices to quantities and vice versa. Knowledge interactions take place among learning and creative agents able to generate new technological knowledge.

The application of interaction models to the economics of innovation and new technology is fertile. The methodology of interaction seems appropriate to implement the large literature that has explored the economics of knowledge. Knowledge interactions are most important and consist in the effects that non-market feedback have upon the capability of agents to generate and use new technological knowledge. Here the frame of standard microeconomics is no longer valid. This happens as soon as we recognize that agents are creative, hence they are credited with the capability to change their own technologies and production functions in response to changes in product and factor markets. Agents are credited with the capability to change their technologies because of knowledge interactions. Knowledge interactions take place in the market place with competitors, providers and customers, in the institutional setting with research and training organizations, financial markets, standardization mechanisms, intellectual property rights regimes (…) and within internal organizations implementing learning procedure.

The results of the empirical analyses of Lundvall (1985) and Von Hippel (1976 and 1998) on the key role of user-producers interactions as basic engines for the generation of new technological knowledge and the eventual introduction of new technologies confirm the relevance of vertical interactions among heterogeneous agents in the generation of knowledge.

Much empirical work have tested and enriched the user-producer interaction approach put forward by Von Hippel and Lundvall to explain the generation of new technological knowledge. Firms can take advantage of interactions both upstream with their providers and downstream with their customers. In this context, the notion of the generative relationship introduced by David Lane and Robert Maxfield (1997) is crucial. Generative relationships are constructive positive feedbacks that lead to the introduction of innovations, and innovations feed structural change in agent/artifact space. The process takes place through a 'bootstrap' dynamics where new generative relationships induce attributional shifts that lead to actions that in turn generate possibilities for new generative relationships. The structural characteristics of the system in terms of the distribution of agents in multidimensional spaces, of their networks of communication, relationship and interactions qualified by aligned directedness, heterogeneity, mutual directedness, permissions and action opportunities, are key elements for the sustainability of the process.

According to Lane and Maxfield the range of generative interactions is much wider than suggested by Von Hippel and Lundvall. Generative interactions take place among firms and other organizations such as research and training centers and universities.

The literature on interactions suffers from two limitations: First, interactions, in general, and specifically knowledge interactions are not free and do not fall like manna from heaven. A cost of knowledge interactions should be identified. It consists of the networking efforts and resources that are necessary to activate and profit form them. Knowledge interaction costs are clearly influenced by the location of each firm with respect to other. Knowledge interactions provide firms with an essential and indispensable input into the generation of new technological knowledge, at costs that are influenced by the network structure of relations among firms. Second and most important, the structure of interactions play a key role in assessing their effects upon the syste. Hence the analysis of knowledge interactions should consider both their costs and their actual effects, as shaped by their strucutre.

The analysis of the origins and possible changes of the structure itself becomes crucial (Antonelli, 2007).

When attention is focused upon the knowledge generation process and the role of knowledge externalities in the provision of knowledge is appreciated as a key factor combined with the intentional participation of the recipients, the notion of knowledge externalities overlaps significantly with the notion of knowledge interaction.

Pecuniary knowledge externalities

A growing attention has been paid, recently, to the distinction introduced by Meade (1952) and Scitovsky (1954) upon two quite different types of 'Marshallian externalities: a) technological externalities and b) pecuniary externalities. Technological externalities consist of direct interdependences among producers. Pecuniary externalities qualify the effects of external conditions upon the full range of price of both inputs and outputs. According to Scitovsky pecuniary externalities consist of the indirect interdependences among actors that take place via the price system. Pecuniary externalities apply when firms acquire inputs (and sell output) at costs (prices) that are lower (higher) than equilibrium levels because of specific structural factors (Antonelli, 2008a and b).

Pecuniary externalities consist of indirect interdependence, mediated by the market mechanisms, via the effects on the price system. Pecuniary externalities exert an effect both on the price of production factors and the price of products. Positive pecuniary externalities are found when the latter are below the equilibrium levels. More precisely, while technological externalities take place when unpaid production factors enter the production function of users, pecuniary externalities apply when the prices of both products and factors differ from equilibrium levels and reflect the effects of external forces above. Pecuniary externalities affect the production function as well as the cost and the revenue functions and consequently have a clear effect on the profit equation.

So far the economics of innovation and knowledge has little used the notion of pecuniary externalities well known by regional economics. As a wide literature in regional economics has shown, the Marshallian analysis of the notion of externalities is much more articulated than the economics of technological spillovers assumes.

The notion of knowledge production function (Nelson, 1982) provides a context into which the role of external knowledge in the endogenous generation of new knowledge can be analyzed with the basic tools of the economics of innovation. The knowledge production function enables to explore the characteristics of the upstream activities that lead to the provision of knowledge inputs to the downstream users in the rest of the system. The inclusion of external and internal knowledge respectively as the two indispensable inputs of a knowledge production and cost function enables to assess the effects of the relative users' cost of each in the generation of new knowledge. In this context pecuniary knowledge externalities enable to appreciate the full range of external effects upon both the exploration, generation and exploitation of technological knowledge.

As far as the exploration activities it is clear that, because knowledge differs from information, technological spillovers do not fall from heaven. External knowledge can be used only after dedicated resources have been invested. Hence external knowledge has a cost, albeit, possibly, lower than internal knowledge. Pecuniary knowledge externalities enable to grasp the effect of this difference in the cost of different forms of knowledge as inputs.

As far as knowledge generation is concerned we see that the combined analysis of the knowledge production function and of pecuniary externalities enables the appreciation of the effects of the external context on the intentional decision-making of firms in the combination of internal and external knowledge inputs in the production of new knowledge. When pecuniary knowledge externalities are important firms have a clear incentive to rely more on external rather than internal knowledge inputs.

Finally, when knowledge exploitation is concerned, we see that pecuniary knowledge externalities make it possible to grasp at the same time the effects of the external context on the prices of knowledge outputs and on the costs of knowledge inputs. The effects of the external context on the cost of external knowledge inputs is usually considered positive, but the effects on the price of knowledge outputs may be negative when knowledge appropriability is considered. Agglomeration and proximity may reduce knowledge appropriability.

A knowledge profit function with pecuniary knowledge externalities enables to grasp the effects of both positive and negative effects. Pecuniary externalities make it possible to appreciate both the positive and negative effects of the external context and their interplay as they apply not only to production functions but also to cost and revenue functions. Hence pecuniary knowledge externalities within a knowledge profit function provide the opportunity to consider both the positive effects of knowledge externalities in terms of lower costs of some knowledge inputs and their negative ones in terms of reduced appropriability of knowledge as an output and hence reduction of the prices for the products that embody new proprietary knowledge. When knowledge is cumulative the dangers of negative pecuniary externalities are clearly most important.

Pecuniary knowledge externalities enable to appreciate the systemic characteristics that favor the generation of technological knowledge. Agglomeration within technological systems both in geographical and technological space, favors the generation of new knowledge only in specific contexts where and when positive knowledge externalities that knowledge as an input make available at costs that are lower than equilibrium levels are not offset by negative externalities that reduce the price that knowledge as an output can command in market exchanges. Such circumstances in fact do not hold everywhere and at all time, but only in highly idiosyncratic conditions (Antonelli, 2005).

The new appreciation of the dynamic effects of pecuniary knowledge externalities, in terms of determinants of the actual capability to introduce new technologies, has pushed more recently much effort to understanding their structural determinants, such as the size distribution of the agents, the size of the aggregations, the network structure of the relations, the distribution of the agents in the space, that qualify the context into which the external effects take place. The notion of threshold becomes central: below (above) some thresholds external effects may be positive (negative). Minimum and maximum levels can be identified with important consequences for understanding how the changing structure of innovation systems has a direct bearing on the rate and direction of technological change (Antonelli, Patrucco and Quatraro, 2008).

In this context a significant overlapping between the notions of knowledge interactions and of knowledge externalities can be identified (Griffith, Redding,Van Reenen, 2003; Lokshin, Belderbos, Carree, 2008). Cingano and Schiavardi (2004) have applied the methodology of social interaction to test the role of knowledge spillovers at the territorial level and show how both intra-industrial knowledge externalities and inter-industrial knowledge externalities have a direct effect on total factor productivity levels of firms. Antonelli and Scellato (2008a) present an empirical analysis of firm level total factor productivity (TFP) for a sample of 7020 Italian manufacturing companies observed during years 1996-2005 and show that changes in firm level TFP are significantly affected by localised knowledge interactions. Such evidence is robust to the introduction of appropriate regional and sectoral controls, as well as to econometric specifications accounting for potential endogeneity problems. Moreover, they find strong empirical evidence suggesting that changes in competitive pressure, namely the creative reaction channel, significantly affect firm level TFP with and additive effect with respect to localised social interactions deriving from knowledge spillovers.

Pecuniary externalities enable to better appreciate the endogeneity of externalities. The levels of pecuniary knowledge externalities in fact are influenced by the density of firms and by the structure of their relations. The quantification and measure of both positive and negative effects, on costs and prices, of the density of firms allows for the identification of the optimum size of clusters.

5. LOCALIZED TECHNOLOGICAL CHANGE

The appreciation of the role of intentional decision-making in the generation of new knowledge and specifically the identification of the inducement mechanism that obliges firms to actually generate new knowledge, qualifies the localized approach.

Agents are characterized by bounded and procedural rationality. Substantial irreversibility qualifies their stocks of tangible and intangible capital. Agents are able to learn by doing and by using: their competence is rooted in their historic context of action. Hence agents are localized and rooted in a limited portion of the geographic, technological, knowledge and competence space. Agents are able to rely upon the web of interactions and externalities that qualify their localized space and much of their actual innovative capability is shaped by their context of action. The quality of the context plays a key role in assessing the actual possibility that the reaction of firms is creative, rather than adaptive.

Out-of-equilibrium conditions and the mismatch between belief and related plans and actual product and factor market conditions push firms to try and modify the decisions that had been taken and the related irreversibilities. Switching costs are necessary in order to cope with the strong and weak irreversibilities that characterize the fixed capital and the reputation of the firm, its location in geographical, technical, and knowledge space, the relations with customers and providers of inputs, the skills of employees and the competence acquired. Switching costs engender opportunity costs. Firms try and innovate in order to save on switching costs. In order to innovate, however, firms need to mobilize their competence and extract new technological knowledge from structured interactions with other creative agents (Antonelli, 1995 and 1999).

Firms are reluctant to change their routines, their production processes, the networks of suppliers and their marketing activities as much as their goals and their understanding of the product and factor markets. In equilibrium conditions, firms are reluctant to innovate because of the intrinsic uncertainty that characterizes both the generation and exploitation of technological knowledge.

Firms innovate when faced with changes in the expected state of the world as generated by changes in both product and factor markets. Innovation is induced by the mismatch between unexpected events that myopic agents cannot fully anticipate and the irreversible decisions that need to be taken at any point in time. Firms induced to innovate by irreversibility and disequilibrium in both products and factor markets search locally for new technologies. The direction of technological change is influenced by the search for new technologies that are complementary to existing ones. In this context the introduction of innovations and new technologies is the result of a local search, constrained by the limitations of firms to explore a wide range of technological options. Procedural rationality, as opposed to Olympian rationality, limits the global search of firms and constraints their search for new technologies in the proximity of techniques already in use, upon which learning by doing and learning by using have increased the stock of competence and tacit knowledge. The rate of technological change in turn is influenced by the relative efficiency of the search for new technologies. This dynamics leads firms to remain in a region of techniques that are close to the original one and continue to improve the technology in use.

Firms are better able to change their technologies when, as a result of effective communication systems, local externalities can turn into collective knowledge; when high levels of investments can help the introduction of new technologies; when an appropriate institutional system of interaction between the academic community, public research centers and the business community is in place; when industrial dynamics in product and input markets can induce localized technological changes that in turn affect the competitive conditions of firms; when stochastic processes help the creative interaction of complementary new localized kinds of knowledge and new localized technologies to form new effective technological systems; when the dynamics of positive feedback can actually implement the sequences of learning along technological paths, as well as the interactions between innovation and diffusion. Such a set of dynamic and systemic conditions has strong stochastic features and is available in finite conditions: the process is unlikely to go on indefinitely until all possible combinations have been exhausted.

The appreciation of the intentional, contextual and resource consuming activity necessary to actually generate new technological knowledge leads to dig deeper into the analysis of the direction or characteristics of the new knowledge being induced and hence generated by firms. Learning firms need to be able to select the direction of their innovation activities. Although learning localizes the cognitive base in a limited spectrum, or ray, from the original focal point of activity, there are still many possible directions along which the generation of new technological knowledge can be aligned. A variety of possible discoveries can be the outcome of the intentional valorization of learning processes and the consequent accumulation of tacit knowledge. New technological knowledge does impinge upon the basic ground provided by learning by doing the current products, learning by using the current technologies and capital goods, learning by interacting with the actual variety of suppliers, competitors and customers. Yet the tacit knowledge and the competence acquired can be implemented and valorized in a variety of possible directions. The choice among an actual array of possible discoveries becomes a crucial issue. The intentional choice of the direction of the possible discoveries marks the second strong departure from the deterministic notion of the firm as an agent moving along a predefined trajectory based upon past learning. As a matter of fact at each point in time the firm has in front a variety of possible directions towards which the creative activities can be ordered. Each needs to be assessed and the relative profitability of the introduction of an innovation needs to be valued both from the viewpoint of the costs of its generation and the revenue stemming from its introduction.

The characteristics of the local context into which firms are embedded provide important help to identify the role of such focusing mechanisms.

In the localized technological knowledge framework of analysis, in order to generate new knowledge, firms need to combine internal sources of knowledge, such as intramuros research and development activities and learning processes, with the systematic use of external knowledge as a primary input for the general production of new knowledge. No firm, in fact, can innovate in isolation. External knowledge is an essential input into the generation of new knowledge. External knowledge can be substituted to internal sources of knowledge only to a limited extent: full-fledged substitutability between internal and external knowledge cannot apply. With proper access to external knowledge firms can complement their localized, internal competence and actually introduce new technologies. Only when a complementary set of knowledge fragments is brought together within a context of consistent interactions, successful innovations can be introduced and adopted: technological knowledge is the product of a collective activity. No firm can claim the command of all the knowledge available. The knowledge external to the firm, at each point in time, is as necessary and relevant complement to knowledge internal to the firm, in order to generate new knowledge. The access conditions to external knowledge are a key conditional factor in assessing the chances of generation of new knowledge. The generation of new knowledge is the specific outcome of an intentional conduct and requires four distinct and specific activities: internal learning, formal research and development activities, and the acquisition of external tacit and codified knowledge. Each of them is indispensable. Firms that have no access to external knowledge and cannot take advantage of essential complementary knowledge inputs can generate very little, if no new knowledge at all, even if internal learning provides major contributions.

In order to better access external knowledge pools however firms can also change their location in knowledge and geographical space. Hence localized technological change consists both of changes in technology and location. Changes in location comprise full-fledged mobility as well as the creation of new links and the connections in the networks of interactions among and within sectors, clusters, and markets.

6. **THE RECURSIVE DYNAMICS OF TECHNOLOGICAL CHANGE**

The recursive and systemic dynamics of technological change can now be explored in more detail. The actual capability of firms to react creatively to out-of-equilibrium conditions, and to change their own technologies depends upon the proper combination of internal knowledge and competence and the localized availability of knowledge externalities and interactions. At each point in time in fact the reaction of firms is qualified and constrained by their location and the consequent conditions of access to external knowledge. When external knowledge cannot be accessed properly, the reaction of firms is adaptive and consists in standard switching upon the existing maps of isoquants.

The creative reaction of firms however consists both in their strategic mobility in multidimensional space and in their innovative capability. Firms can change their location, enter and exit product and factor markets, create new links and communication channels, change their position in vertical inter-industrial linkages and in regional districts and do change their knowledge base, hence their complementarities with respect to other firms. Firms can introduce institutional innovations that help the emergence of new markets and new forms of organization of the system at large, such as in the case of venture capitalism.

Their reaction can become creative as opposed to adaptive and engender the actual introduction of successful, productivity enhancing innovations, when and if the interactions and feedbacks shaped by the structure of the system provide the access to external knowledge and external learning conditions. The intensity and the effects of interactions are shaped by the structure of the system and specifically by the network topology of agents distributed in the multidimensional space, at each point in time. The distribution of agents in the multidimensional space is itself the endogenous result of the locational strategies of agents carried out in the past. Clearly externalities are internal to the system: they depend upon the specific combination of activities and channels of communication in place among them. Externalities depend upon the structure of the system. The structure of the system into which firms are localized exerts a key role in shaping the dynamics both at the aggregate and the individual level.

Traditionally the notion of economic structure pays attention to the sectoral and regional composition of economic systems. The analysis of the structural composition of the system, its effects on the conduct of firms and its evolution initiated by Simon Kuznets (1930, 1955, 1966, 1971, 1973) can be retrieved and enriched by the appreciation of other structural characteristics.

Industrial economics has explored the characters of the industrial structure in terms of market concentration, barriers to entry and to mobility. The analysis of the vertical structure of industrial and economic systems has appreciated the role intersectoral linkages as vectors of input flows and identified the central role of key sectors in the dissemination of pecuniary and technological externalities. Economic geography has explored successfully the central role of regional districts and clusters as forms of governance of economic activity. Finally the changing patterns of consumption and the endogenous evolution of tastes and preferences, since the identification of the Engel's curves, have been the object of much empirical and theoretical work.

The analysis of the dynamics of knowledge networks, the governance of knowledge interactions, and of the structure of social, non-market interactions that take place within knowledge networks, innovation systems and clusters is consistent and complementary with the analysis of structural change initiated by Simon Kuznetz. Actually it can enrich and rejuvenate this line of enquiry so as to capture their role in the generation of new technological knowledge and integrate it into the array of other structural determinants of the conduct of firms. such as endowments, industrial, sectoral, regional and economic structure, market forms and organization of the networks of knowledge communication and interaction in place,

These structural characteristics of the system are the features of a rugged landscape into which firms are rooted and change as a result of effects of the strategic conduct of agents and the resulting collective action can introduce at each point in time. They change through time, albeit at a slow rate, as a result of the dynamics of agents and of the aggregate. The meso-economic characteristics of the system act as a filter between the dynamics at the individual and the aggregate levels (Dopfer, 2005). The key point remains in fact that the changing structure of the system endogenous to the system itself: the architecture of knowledge networks, as well as the industrial, sectoral, regional and economic structure is heavily influenced by the strategies of firms seeking to improve their location within systems of interactions.

According to Paul Krugman (1994) such rugged landscapes in geographical, technological, knowledge, market and product space are at the same time the consequence and the determinants of complex dynamics. This approach makes it possible to pay attention to the structural characteristics of the system in terms of the distribution of agents in the different space dimensions, and to appreciate the architecture of the relations of communication, interaction and competition that take place among agents in assessing the rate and direction of technological change.

The structure of interactions and the flows of knowledge externalities within and among sectors and markets, the forms of competition that prevail in each of them, the geographical distribution of firms, their density in regional and technological clusters, the forms of organization within and among firms, the shape and structure of knowledge networks, the vertical organization of industrial filieres, the governance mechanisms, the institutional context are the meso-economic carriers of history and, as such, embody the memory of the system.

It is clear that positive feedbacks take place only in specific circumstances: some structures are more conducive than others. In some circumstances structural change leads to forms of organized complexity where the reaction of firms become actually creative and leads to the introduction of innovations.

When positive feedbacks qualify the individual reaction of a firm into a creative process, a collective process of generation of new technological knowledge takes place and leads to the eventual introduction of a new technology. It is clear in fact that the larger is the number of firms that are induced to react creatively and the larger is the amount of technological knowledge that is generated in the system. In such conditions not only a larger number of firms is induced to try and change its technology, but also a larger amount of knowledge is being generated. The chances that the reaction of firms becomes actually creative and can actually lead to the introduction of successful technological innovations that increase the levels of total factor productivity in turn increase. The rate of technological change as a consequence, is likely to increase. High levels of complementarity and convergent innovative efforts characterize the direction of the new technologies being introduced. New gales of systemic innovations are likely to emerge as the consequence of a sustained chain of positive feedbacks. When the interplay between strategic and knowledge interactions is fertile, the dynamics of positive feedback is sustained and the introduction of innovations drives further innovations.

When the structure of the system is such that knowledge externalities are not available or are out-weighted by significant transaction, search and communication costs, when congestion and limited appropriability impede the use of external knowledge do not take place and the architecture of interactions is not able to integrate strategic and knowledge interactions in a fruitful way, single innovations can remain isolated acts of a minority of individual firms with little systemic effects. When knowledge social interactions are missing and the competitive threat to established market position is weak and hence creative social reactions are not solicited, inferior technologies are likely to be resilient. Adaptive responses, as opposed to creative ones, are likely to occur when firms have not access to knowledge social interactions and the generation of knowledge should rely only upon internal sources. Firms are not able to introduce new localized, productivity enhancing technologies and may prefer to switch, i.e. just to change their techniques within the existing maps of isoquants. When the access of firms to external knowledge is costly if not inhibited, and adaptive responses, as opposed to creative ones, prevail, no technological change takes place and hence the structures of the system do not change.

The national system of innovations approach framed by Nelson (1993) and widely used and implemented, contributed widely to appreciate the key role of the structural characteristics of economic systems in shaping their innovative capability, but clearly suffers from the basic assumption that the structure of the system is either given or exogenous. In this line of enquiry there is no effort to grasp the endogenous determinants of structural change. Our approach makes it possible to focus the attention on the intertwined dynamics of knowledge externalities and interactions, localized technological changes and structural change.

The localized introduction of localized productivity enhancing technological changes takes place when knowledge externalities and interactions qualify the creative reaction of firm and enable positive feedbacks. In turn localized technological changes affect the structure of the system and hence the flows of knowledge externalities and interactions and ultimately the extent to which feedbacks are positive. The introduction of new technologies as well as the array of strategic conducts that firms experience in the system impact and change the structure of the economic system.

Because knowledge interactions and externalities, and hence positive feedbacks, are not exogenous, the amount of knowledge externalities and interactions depends upon the structure of the system. The structure of the system is determined by the conduct of firm including both market strategies, the introduction of innovations and new communication and interaction networks. The activation of knowledge interactions is the result itself of intentional action.

At each point in time, in fact, agents can change both their production and utility functions and their location. Agents are mobile, albeit in a limited range constrained by relevant switching costs, and they can change their production and utility functions, building upon their experience and competence based upon learning processes, hence in a limited span of techniques and preferences practiced in their past. Firms select their interacting partners, build communication channels, elaborate governance mechanisms that favor knowledge interactions. At each point in time the map of multidimensional space into which each firm is embedded is exposed to the changes brought by the changing location of firms. Firms are both creative with respect to their technologies, and mobile, with respect to their location in the space of knowledge, technologies, and reputation, hence they can change the structure of the system. The introduction of institutional changes adds on to the endogenous evolution of economic structures.

Intellectual property right regimes play a key role in assessing the actual conditions to accessing existing knowledge by third parties as they affect the knowledge governance both in terms of the actual levels of the total costs for the perspective users of external knowledge and the appropriability of the new knowledge generated. All changes in the institutional regime that articulates the intellectual property conditions affect directly the amount of net positive knowledge externalities available in a system.

Antonelli and Teubal (2008 and 2009) have shown how venture capitalism has changed the structure of interactions and transactions in financial markets with important effects upon the capability to fund, select and exploit new technological knowledge. Venture capitalism itself is a major institutional and organizational innovation that has activated a new mechanism for the governance of technological knowledge. Venture capitalism is the result of a system dynamics where a variety of complementary and localized innovations introduced by heterogeneous agents aligned and converged towards a collective platform. The new mechanism favors the creation of new science based start-up and has lead to the creation of new, dedicated financial markets. These new financial markets, specialized in the transactions of knowledge intensive property rights, combine the advantages of polyarchic decision-making in screening and sorting radical innovations with the direct participation to the profits of new outperforming science-based start-up typical of the corporate model.

Antonelli (2008b) has shown that when firms are able to align their research strategies so as to take advantage of locally abundant knowledge, the amount of knowledge generated is larger. The amount of external knowledge that has been used in the knowledge generation process has a direct bearing not only upon the amount of knowledge being generated and hence on the efficiency shift engendered in the production process, but also on its characteristics. Firms that rely more upon external knowledge are more likely to produce complementary knowledge.

As Figure 3 shows, each firm directs the generation of technological knowledge in a simple Lancastrian knowledge space with two characteristics (X_1 and X_2) depending on the opportunities to benefit from the locally available pecuniary knowledge externalities (Lancaster, 1971). At time 1 each firm moving respectively from point A, B, C, directs its technological strategy either towards either D or E, F or G, H or I depending on the conditions of the external context. In turn, once rooted in either point, new possible directions can be chosen, within corridors defined by the firm's internal characteristics that include the preceding path.

The technological path of each firm reflects the characteristics of both its own internal quasi-irreversibilities and learning processes and the local context. The initial conditions play a key role in defining the context of action. The external context however, at each point in time, has powerful effects on the dynamics. According to the quality of knowledge interactions, some directions are favoured and others impeded. In Figure 3 the firm in A is induced to direct its innovation process towards E rather than D. The firm in B would move towards F rather than G. If other firms act as firms A and B the structure of the existing network LMMNOP will change. A new architecture of the network emerges. Its governance will change according to the ability of each new and old member respectively to enter and to participate to the new communication flows within the new architecture of the network.

By no means the new structure of the network is bound to be superior to the previous one. If the structural change increases the actual amount of knowledge externalities and interactions, a self-propelling process takes place. As long as additional changes reinforce this dynamics and consolidate the network each the process gains momentum.

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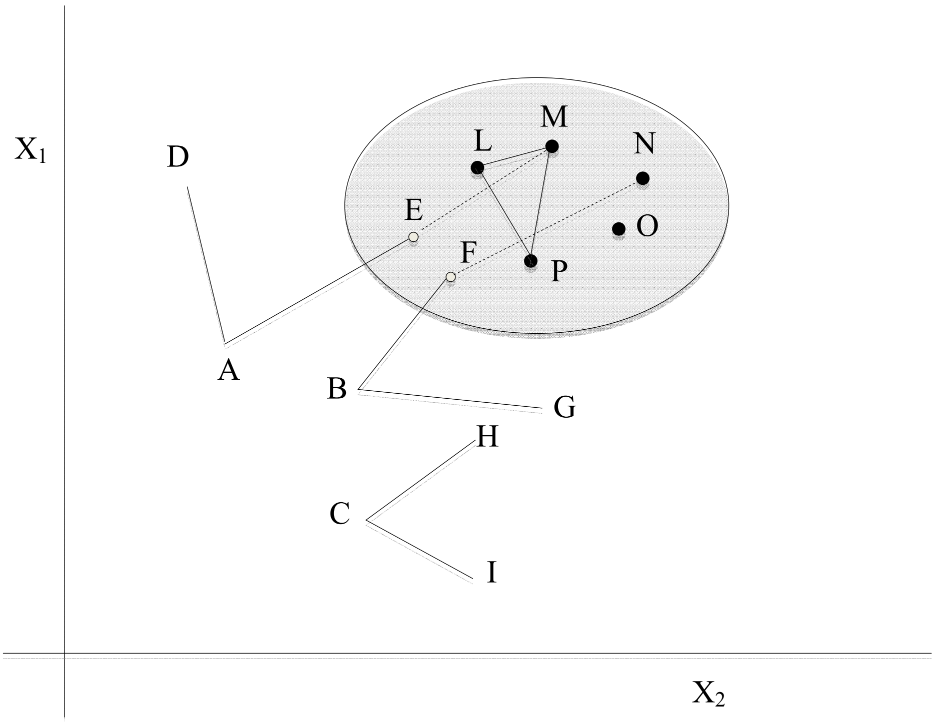
FIGURE 3. THE DIRECTION OF TECHNOLOGICAL OF KNOWLEDGE



Positive feedback is likely to reinforce the process as the effort to increase the complementarity of each firm's research activity reinforces the local pools of knowledge that, in turn, increases the possibility to access external knowledge. At the same time increasing awareness of the opportunities for better knowledge exploitation provided by the intensive use of locally abundant and idiosyncratic production factors increases the intentional convergence of knowledge generation strategies towards a common direction shaped by the collective identification of the local idiosyncratic inputs. At the population level, the effects of individual convergence are reinforced by selection mechanisms. The success of the localized knowledge exploitation strategies acts as a powerful focusing mechanism that, through selection processes, favors the survival and growth of firms that have selected convergent paths of knowledge generation and exploitation (Antonelli, 2009b).

Each firm engaged in generating new knowledge and appropriating its benefits in terms of extra-profits, discovers that the convergent alignment of its internal research activities with the complementary research activities of other firms, co-localized in both geographical and knowledge space, is a powerful factor of competitive strength. It is immediately clear in fact that the lower the unit costs of external knowledge are, the larger is both the amount of knowledge that the firm is able to generate and the larger is its localization in a specific context. A firm that is located in a conducive knowledge environment, and is able to identify and access the local pools of knowledge at low cost, is induced to take advantage of it and hence to base the generation of its new knowledge in the characteristics of its environment. This in turn is likely to affect the architecture of the local pools of knowledge and their governance.

The changes in the structure of the system have a direct bearing upon the amount and the quality of externalities and social interactions, and specifically knowledge externalities and knowledge interactions that make available to each agent. The endogenous and dynamic character of externalities is set. New structures emerge and with them new architectures of externalities, communication and interactions. These in turn affect the dynamics of feedbacks and ultimately convert the chances that the creative reaction of firms leads to the actual introduction of productivity-enhancing innovations.

The industrial structure of the system is changed by the emergence of new industries both upstream and downstream with important effects for the system at large. New markets become effective with new opportunities for supply and demand to interact and new possibilities for division of labor and specialization. New flows of intraindustrial externalities may be caused, while others may be hampered by the structural changes.

The dynamic coordination of creative agents emerges as a key issue. At the system level the creation of platforms that enable to implement the dynamic complementarities of firms helps the emergence of clusters and favors the intensification of knowledge interactions and hence the rates of introduction of localized technological changes. At the firm level the counterpart consists in the design and implementation of dedicated governance mechanisms to implement knowledge interactions such alliances, technology clubs, long term contracts.

Innovation systems emerge, articulated in horizontal and vertical blocks of industrial sectors and filieres, technological districts, clusters, and networks when the generation of new technological knowledge is reinforced by the emerging structure of complementarities based on communication channels provided by the intentional research strategies of firms that discover new sources of complementarities and move within the knowledge space. The active role of the lead users and their fruitful interactions with their customers are encapsulated in these structures of the systems. The institutional features of the system complement the geographical and industrial ones and qualify the characterization of the mesoeconomic structure of the economic system.

The successful accumulation of new technological knowledge, the eventual introduction of new and more productive technologies and their fast diffusion are likely to take place in a self-propelling and spiralling process and at a faster pace within economic systems characterized by fast rates of growth where interaction, feedbacks and communication are swifter. In such special circumstances, the system can undergo a phase transition leading to the introduction of a new radical technological system.

In special circumstances structural change leads to the emergence of strong innovation systems empowered by highly performing network structures that are the result of the collective dynamics of a myriad of agents in search of potential, vertical and horizontal- complementarities. The emergence of highly performing innovation systems may lead to Schumpeterian gales of innovations. Within local and sectoral systems of innovation the architecture of the communication channels that link each agent to other, the distribution of nodes can be seen as the result of an endogenous process of emergence that shares the complex dynamics of Internet network creation (Pastor–Satorras and Vespignani, 2004; Antonelli, 2007).

The evolution of these networks can exhibit both positive and negative features. Scale free networks may emerge and favor the access to external knowledge for a variety of actors. Some firms can emerge as the stars of the system as they are able to act as general switchboards of the communication flows (Barabàsi, and Albert, 1999; Barabàsi, Jeong, Neda, Ravasz, Schubert, and Vicsek , 2002; D'Ignazio and Giovannetti, 2006).

The articulation and the structure of networks within and among sectors, clusters and filieres is the result of a collective process. Each firm is able to move in such a knowledge space and generate new knowledge taking advantage of increased proximity and reinforced communication and interaction channels with other firms clustering in nodes (the shaded region of Figure 3) where potential knowledge complementarities can be better understood. As a result, new systems of innovation based upon nodes of coherent knowledge complementarity emerge (and others decay) while the direction of technological knowledge is shaped by the emergent collective convergence of the research strategy of each firm.

Among the possible consequences, however, it is clear that, at the system level, the mix of activities that engender knowledge externalities and interactions may deteriorate over time: the entry of new members in the network as well the changes in the governance of the networks may cause congestion so as to lead to the actual decline of the amount of knowledge externalities and interactions available within the local system.

Each agent is both myopic and localized in a limited region of the space, hence it is not able to make a global choice. Entry in a network may improve its own individual chances to access external knowledge but engender a decline in the overall viability of the innovation system.

Agglomeration within clusters in the long run may engender negative effects. Knowledge governance costs may increase along with the number of firms accessing the same knowledge pools because of congestion effects in coordination. Eventually density may have negative effects in terms of reduced knowledge appropriability: the case of excess clustering can occur when proximity favors the uncontrolled leakage of proprietary knowledge within the local system (David, Foray, Dalle, 1995; Antonelli, Patrucco, Quatraro, 2008).

The convergence of the direction of technological change and the emergence of innovation systems in geographical and technological space occurs as long as the positive effects of knowledge interactions are larger than their negative effects. In specific contexts the interplay can lead to logistic processes of emergence with S-shaped dynamic processes that identify critical masses.

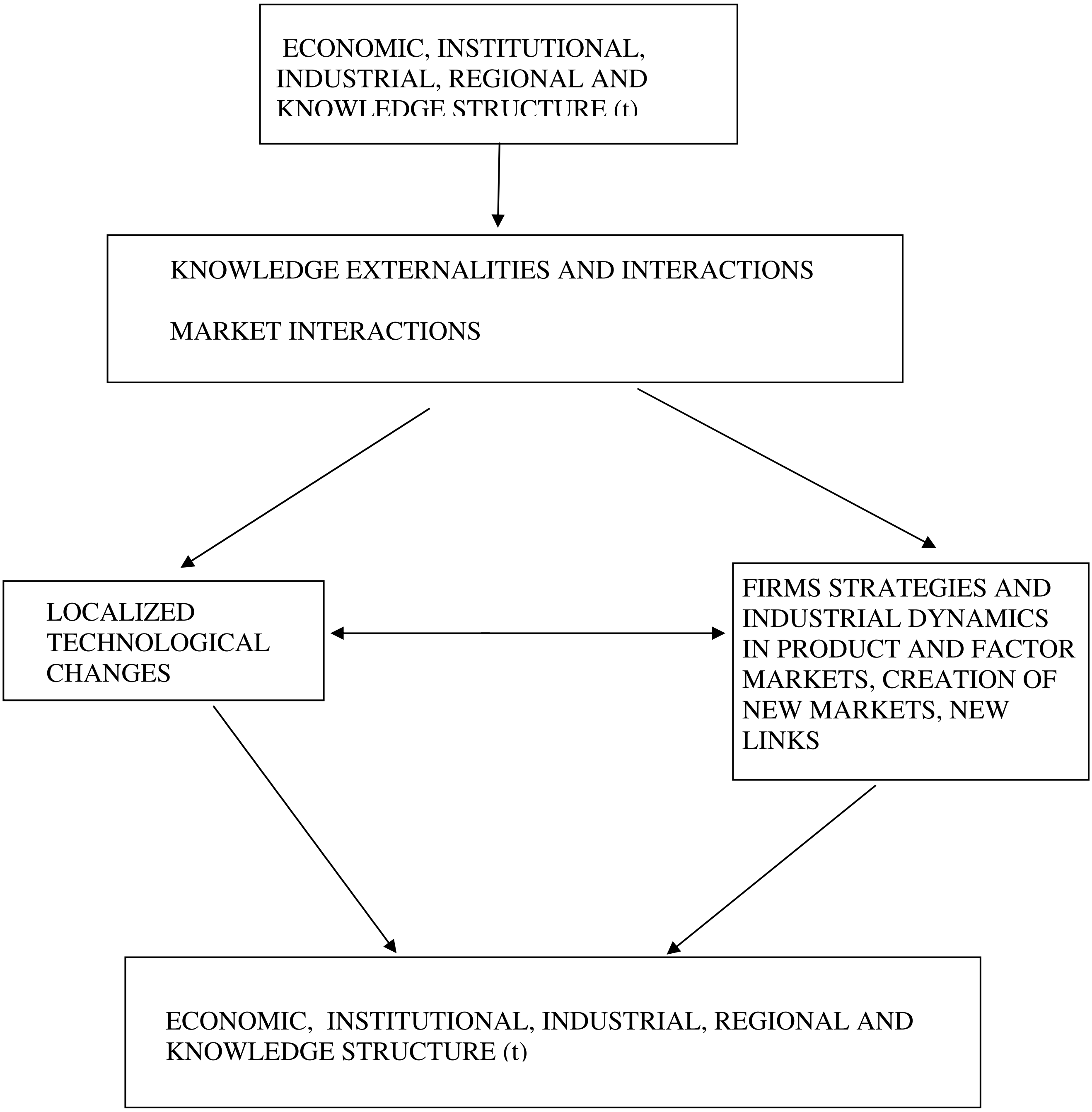
At each point in time the emergence of new innovation systems may be blocked by a number of countervailing forces. The process is far from being past dependent: it is shaped, at each point in time by the ability of the actors to contrast the dissipation of pecuniary externalities. Both at the firm and the regional level these processes are likely to occur with a strong non-ergodic and sequential stratification (David, 1994). The path dependent dynamics stems from the interplay between past dependence and intentional action. The internal stock of knowledge acquired through learning by each firm together with the features of the local pools of knowledge and of the economic structure is the past dependent components as at each point in time they are the result of historic accumulation. The amount of knowledge being generated, the direction of technological change being introduced, the levels of knowledge governance costs and the price of locally idiosyncratic production factors are, at each point in time, the result of the intentional action of agents. Hence they provide the opportunities for intentional action to change the original path. At each point in time the intentional action of the embedded agents adds a new layer to the original structure: the original shape exerts an effect that the new layers can modify, depending on their thickness and density. Each firm in fact is able to interact with the system and to change it. This occurs at different levels: by introducing changes to the structural conditions and the topology of the system's communication channels, with the introduction of organizational innovations in knowledge governance mechanisms, and by changes in the factor markets due to innovations that change the supply of the idiosyncratic production factors. The emergence and decline of innovation systems is the result of continual feedback between the structure of the system and the innovative action of its agents.

When the negative effects of agglomeration exceed the positive effects, the mobility of firms in geographical and knowledge space is centripetal and leads to divergent path of exploration. Firms leave existing pools of knowledge and search for new possible agglomerations around new platforms and other sources of knowledge complementarity. Mutation can be an important alternative. In this case firms are able to shift the factors of complementarity yet retaining proximity. When mutation takes place clusters of firms exhibit geographical stability but changing organization and focus of knowledge interactions.

Externalities are endogenous and dynamic. Their dynamics is characterized by non-ergodicity. The past has a consequence on the future. Such non-ergodicity however cannot be characterized as sheer past-dependent.

Structural and technological changes interact and shape at each point in time the new architecture of the structure into which firms are localized. The new structural conditions shape the creative reaction of firms as well as their strategies. These in turn change the structure of the system. The key determinants and characteristics of system dynamics of technological change are set. Technological change and structural change are intertwined and mutually interdependent. The introduction of innovations is part of a more general and dynamic process of self-organization of the structure of the system.

FIGURE 4 THE EVOLVING INTERACTION BETWEEN TECHNOLOGICAL AND STRUCTURAL CHANGE



7. PERSISTENCE, PAST DEPENDENCE AND PATH DEPENDENCE

Historic analysis provides the key information to understand the determinants of the long-term dynamics of economic processes. This is true both at the microeconomic, mesoeconomic and macroeconomic level. Historic analysis reveals the features of the quasi-irreversibilities that shape much of the tangible and intangible assets of firms. Historic analysis provides key information to grasp the mesoeconomic features of the systems in terms of the economic, industrial and regional structures, the composition of preferences and tastes of consumers, the architecture of the networks within and among sectors, clusters and filieres into which firms are embedded and the amount of knowledge externalities and interactions that are available to each of them. Finally, historic analysis provides the key elements to understand the processes that shape the reactions of agents and make them creative, as opposed to adaptive and hence make the actual introduction of innovations possible.

At each point in time the historic processes that have defined the present conditions of each agent characterize their conduct including their capability to innovate. Hence, at each point in time, firms and agents can change their location in space, their competence, their access to external knowledge, their systems of interactions. In so doing agents can change the structural conditions of the systems.

The introduction of innovation and the related generation of new knowledge is shaped by cumulative forces, substantial irreversibility and positive feedbacks only when a set of qualified circumstances applies. Hence innovation is expected to be a persistent process that is reinforced by external feedbacks and contingent factors only when the interplay between technological and structural change sustains the capability of firms to introduce innovations. The dynamics of positive feedback in fact is far from linearity both with respect to an array of factors such the density of agents, the architecture of their relations, the quality of communication channels the conditions at which the communication hubs work. Beyond some –changing- levels, congestion, exclusion and saturation may take place and negative externalities become larger than positive externalities.

Both centripetal and centrifugal effects characterize these dynamic processes with major effects in terms of discontinuity. Centripetal effects are found when the convergence towards local attractors is stronger than divergence. Technological districts, knowledge platforms and networks, new vertical filieres emerge and favor the persistence of the rates of introduction of innovations. When centripetal effects prevail the rates of introduction of innovations are stronger. At the system level growth rates increase together with the variance of the performances of firm's. Eventually the diffusion of technological and organizational innovations exerts a strong effect in terms of reduction of the spatial and economic dispersion of firms. Centripetal forces prevail when congestion and knowledge dissipation cause negative net externalities that prevent the creative reaction of firms. Adaptive responses prevail and firms prefer to switch upon the existing maps of isoquants and are no longer able to change them. The rates of growth of the system decline as well as the variance in the performances and in the characteristics of the firms. The distribution of firms in regional and knowledge spaces tends towards higher levels of homogeneity.

The persistence of the innovative activity takes place when A) the competitive pressure pushes firms to react by means of more than traditional price-quantities adjustments but to try and change their technologies. Firms can actually react creatively to face unexpected events by means of the introduction of new technologies and new organizational methods and introduce successful innovations when two conditions are fulfilled: B) they are actually able to learn to learn and C) the external context qualifies the intentional action of firms and provides the access to complementary and indispensable inputs in terms of external knowledge. In such cases the dynamic process is likely to be characterized by significant hysteretic, non-ergodic features.

This dynamics in fact is characterized by recursive feedbacks. The introduction of new technologies and new organizations methods affects the systems on two counts as it engenders further waves of unexpected events and Schumpeterian rivalry, and, at the same time, makes available new knowledge spillovers. Hence the introduction of innovations can be considered as the persistent and emerging property of an economic system where the interdependence between the dynamics of learning, internal to firms, and the evolving structure of interactions among firms that determines the actual amount of external knowledge available within the system, exert path dependent, rather than past dependent, effects. Non-ergodic dynamics in fact can be either past dependent or path dependent: in the latter case the effects of hysteresis are qualified and shaped by the localized context of action. In the former the process is shaped by the initial conditions only (Antonelli, 2008).

When a process is non-ergodic, initial conditions exert their effects without alteration upon the full sequence of developmental steps and hence on the final outcome. Past dependence, or 'historicity', is an extreme form of non-ergodicity. Historic, as well as social and technological, determinism fully belongs to past dependence. Here, the characteristics of the processes that are analysed and their results are fully determined and contained in their initial condition.

In our approach, instead, it is clear that small and contingent events may change the fragile set of conditions that favor the persistence of innovation because of structural changes that undermine the prevalence of positive knowledge externalities and with them the chances that firms are actually able of creative, as opposed to adaptive, reactions. This process is characterized by historicity, as such however, it may exhibit strong discontinuities. The direction of the process, moreover, may be influenced by the sequential emergence of contingent factors that can modify the path shaped by quasi-irreversible factors. Both the rate and the direction of technological change are affected by the combination of hysteresis and flexibility. The process is indeed path-dependent rather then past-dependent.

Path dependence is the specific form of complex dynamics applied to evolving economic systems. Path dependence provides a unique and fertile analytical framework which is able to explain and assess the ever-changing outcomes of the combination of and interplay between factors of continuity and discontinuity, growth and development, hysteresis and creativity, routines and 'free will', internal and external factors which all characterize economic action in a dynamic perspective that is also able to appreciate the role of historic time.

According to Paul David, path dependence is an attribute of a special class of dynamic processes. A process is path dependent when it is non-ergodic and subject to multiple attractors: 'Systems possessing this property cannot shake off the effects of past events, and do not have a limiting, invariant probability distribution that is continuous over the entire state space' (David, 1992: 1; David 1988; David, 1994; David, 2007).

Indeed, historic analysis and much empirical evidence in economic growth and specifically in the economics of innovation and new technologies confirm that these characteristics apply and are most relevant to understanding the laws of change and growth of complex systems. Path dependence is the specific form of complex system dynamics most apt to understand the process and the outcomes of the interactions among myopic agents embedded in their own context and constrained by their past decision, yet endowed with creativity and able to generate new knowledge by means of both learning and intentional innovative strategies as well as through structural changes. Path dependence differs sharply from past dependence.

In the theoretical economics of innovation, past dependence has often been assumed: the epidemic models of the diffusion of innovations and the notion of innovations 'locked in' a technological trajectory are typical examples of the deterministic representation of essentially stochastic technological and social phenomena. The notion of technological trajectory is another example of extreme past dependence. The development and implementation of a new technology would follow a well defined and pre-determined sequence of steps that are all defined by the initial characteristics. The notion of technological trajectory is a typical example of the so-called technological determinism according to which technology changes according to its internal rules and while it is able to have important effects on the economic system there is possibility for the on-going changes in the economic system to affect the sequence of innovations that characterize its evolution.

As such, these non-ergodic models are analytically informative but empirically uninteresting. The process takes place within a single corridor, defined at the outset, and external attractors cannot divert its route, nor can the dynamics of the process be altered by transient random disturbances in its internal operations.

Path dependence differs from deterministic past dependence in that irreversibility arises from events along the path, and it is not only the initial conditions that play a role in selecting from among the multiplicity of possible outcomes. The analysis of a path-dependent stochastic system is based on the concepts of transient or 'permanent micro-level' irreversibilities, creativity and positive feedback. The latter self-reinforcing processes work both through the price system and by means of pecuniary externalities and social, strategic and knowledge interactions. The conceptualization of stochastic path-dependence can be considered to occupy the border region between a view of the world in which history is relevant only to establish the initial conditions, but has no bearing on the developments of the process and another where the dynamics unfold deterministically.

Path dependence takes place when events that occur along the process can have long lasting consequences and divert both its rate and its direction. A path-dependent process is a non-ergodic process that is not fully determined by its initial conditions: it allows for the contingent effects of localized events that may change the rate, the direction and the sequence of events.

Path dependence is the conceptualization of historical dynamics in which one 'accident' follows another relentlessly and unpredictably and yet the past narrows the scope of possible outcomes, shaping the corridor into which the dynamics takes place. Path dependence gives economists the scope to include historical forces without succumbing to naive historical determinism. At the same time it makes it possible to reduce the ray of the relevant spaces into which the system is likely to move at each point in time. The understanding of the historic forces the dynamics of both individual agents and aggregate system provides a clue to foresee, with some degree of indeterminacy, the future developments of a dynamic process. In so doing path dependences make it possible to substitute the deterministic fallacy of general equilibrium analysis with the stochastic understanding of long term dynamic processes.

The analysis of the structural determinants of the rate and the direction of technological change enables the identification of the path-dependent interplay between structural and technological change. Technological change can alter the characteristics of the system and yet it is itself the product of the characteristics of the system at each point in time. A strong common thread links the analyses developed with the notion of life cycle and technological trajectory and the notion of path dependence. Only the latter, however, provides a theory to understand why and how technological change takes place sequentially along axes defined in terms of complementarity and cumulability, both internal and external to each firm. From this viewpoint the technological path represents significant progress with respect to both the technological trajectory and the life cycle.

Path dependence applies both to each agent and at the system level: hence we can identify and articulate an individual and a systemic path-dependence. Individual path-dependence provides the tools to understand the combination of hysteretic, past-dependent factors such as the quasi-irreversibility of tangible and intangible production factors, stock of knowledge and competence, and localized learning, with the generative relationships and creative reactions that make possible, at each point in time, a change in the direction of the action of each agent, including the introduction of innovations. At the firm level the generation of knowledge shares the typical characteristics of a path-dependent process where the effects of the past, in terms of accumulation of competence, mainly based on processes of learning in a localized context and interaction with a given structure of agents, exert an influence and yet are balanced by the specific creativity that is induced by the changing conditions of the system. Systemic path dependence defines the elements of non-ergodicity that characterize the changes in the industrial, regional and economic structure of the system including the architecture of the networks of social, knowledge and strategic interactions.

The notion of path dependence provides one of the most articulated and comprehensive frameworks from which to move towards an analysis of the conditions that make it possible to conceive the working of an economic system where agents are able to generate new technological knowledge, introduce new technological innovations and exploit endogenous growth. The notion of path dependence can be considered the analytical form of complexity most apt to understand the dynamics of economic systems where heterogeneous agents are characterized by some level of past dependence, as well as by local creativity, interdependence and limited mobility in a structured space that affects their behaviour but is not the single determinant.

Path dependence is an essential conceptual framework that goes beyond analysis of static efficiency and enters the analysis of the conditions for dynamic efficiency. It applies to each agent, in terms of the quasi-irreversibility of their own endowment of tangible and intangible assets, networks of relations in both product and factor markets, stock of knowledge and competence, and to the system level in terms of general endowments of production factors, industrial and economic structure, and the architecture of the networks in place.

The identification and articulation of individual and system path-dependence makes it possible to catch the basic laws of the continual interaction between the hysteretic effects of past dependence, both at the agent and at the system level, and the feedback dynamics that allows the intentional conduct of the creative agent to change both the course of their actions and the characteristics of the structured space. In so doing, path dependence retains the positive contributions of complex dynamic system methodology, and at the same time has the capability to overcome the intrinsic limitations stemming from its origins built on natural sciences where human decision-making is not considered. Indeed, the notion of path dependence is one of the main forays in the challenging attempt to apply the emerging theory of complexity to economics.

8. CONCLUSION

Standard economics assumes that utility and production functions are exogenous or, at best, change smoothly and evenly following the rates of learning processes and ubiquitous positive externalities. In evolutionary economics the introduction of innovation is assimilated to the result of random mutations, as such it is not investigates. No clues are provided to understand the historic, regional and institutional determinants of the generation of innovations. By contrast the selection of innovations is analyzed as the result of a systemic process.

Complex system dynamics elaborates the view that change and dynamics are intrinsic to systems characterized by the variety and creativity of their components. Complex systems are characterized by the heterogeneity of agents with different functions, different endowments, different learning capabilities different goals and different perspectives, and most important different locations in the multidimensional spaces of geography, knowledge, technology and reputation. These heterogeneous agents are complementary components of the system and their action can affect the dynamics of the system. The working of each of them as well as the working of the system can be understood only if the web of interactions and interdependencies are identified and qualified in terms of organized complexity.

The merging of the theory of complexity with economics can provide a frame of analysis into which the system dynamics of technological change can be better understood, but only if the microeconomics of innovation is fully elaborated and integrated and the relations between individual and systemic change respectively at the micro and macro level are clearly articulated.

The theory of complexity has two major limitations. First it suffers from the poor exploration of the determinants of economic action and the inadequate appreciation of the role of rent-seeking intentionality in the decision-making of economic agents. Economic agents are too often portrayed as if their choices, including the choice whether to innovate or not and in which direction, were irrelevant. Second it misses an economic understanding of the determinants of the characteristics of the systems that qualify as organized complexity. Much complexity thinking risks to accept that such characteristics are either given or exogenous.

The integration of the economics of innovation and the theory of complexity enables to consider economic systems as complex dynamic mechanisms where innovation is an emerging property of the system. The actual rates and direction of change are determined by the matching between the response of creative agents anchored in a well portion of space by the quasi-irreversibility of their tangible and intangible inputs, and exposed to endogenous events that alter the expected conditions of product and factor markets, and the structure and quality of knowledge externalities and interactions that make external knowledge accessible within the system, according to its structure. The quality of the localized context of action is crucial to enable the creative, as opposed to adaptive, reaction of firms.

Table 3 provides a synthetic account of the building blocks of our analysis. The vertical axis highlights the three basic assumptions of the theory of complexity about the basic features of the agents: economic agents and specifically firms are qualified by their capability: a) to react to unexpected changes in product and factor markets, b) to interact and c) to bear the effects of irreversibility. The horizontal axis presents the three dimensions of the generation of knowledge, the introduction of technological and structural changes. The diagonal highlights the three basic properties of the system dynamics of technological change, respectively: the learning capability of agents, innovation as an emergent property and the key role of organized complexity.

The table enables to synthetize the analysis carried out in the chapters. Out-of-equilibrium conditions push agents to react (Chapter 3). Their reaction builds upon the localized learning processes. It can lead to the actual introduction of productivity enhancing innovation if and when the local context is structured as an organized complexity where knowledge feedback, interactions and externalities support the innovative effort of firms (Chapter 4). The introduction of innovations is an emergent property of an organized complexity that brings together the individual efforts and the quality of the contextual feedbacks (Chapter 5). The introduction of innovations in turn affects the structure and architecture of the local innovation systems (Chapter 6). New innovation systems emerge and other decline. Resilience and persistence both at the system and the firm level shape the change of the structure of the system and lead to path dependent dynamics (Chapter 7).

Although agents are qualified by their ‘reactivity’ their individual reaction, when caught in out-of-equilibrium conditions, is not sufficient to generate new productivity-enhancing innovations. The actual introduction of an innovation by an agent in the economic system depends upon an array of contextual conditions such as knowledge interactions and externalities that enable the internal competence of each firm to actually generate an effective artifact that is able to produce more with the same amount of inputs. The internal generation of new technological knowledge is augmented and the internal sources of competence are stirred by the access to external knowledge. Positive feedbacks consists in the process by means of which the reaction of an agent caught in out-of-equilibrium conditions is actually creative, as opposed to adaptive, and, as such, is able to lead to the introduction of actual productivity-enhancing innovations in the system.

TABLE 3. A SYNTHESIS OF THE FRAMEWORK

	KNOWLEDGE GENERATION	TECHNOLOGICAL CHANGE	STRUCTURAL CHANGE
REACTION	LOCALIZED LEARNING	LOCAL SEARCH	OUT-OF-EQUILIBRIUM CHANGES IN PRODUCT AND FACTOR MARKETS
EXTERNALITIES, INTERACTIONS & FEEDBACK	FROM ADAPTIVE TO CREATIVE REACTION	LOCALIZED TECHNOLOGICAL CHANGE	EMERGENCE AND DECLINE OF INNOVATION SYSTEMS
IRREVERSIBILITY	CUMULABILITY	SWITCHING COSTS, PERSISTENCE	RECURSIVE PROCESSES, PATH DEPENDENCE, ORGANIZED COMPLEXITY

Some mesoeconomic architectures are clearly more conducive than others. Some knowledge structures enable the dynamics of positive feedbacks. With other structures knowledge dissipation may prevail. The architectures of the structural characters of the system may exhibit high levels of resilience, yet are not given. They are themselves the path-dependent products of the intentional choices of location and mobility of agents as well as of their collective interaction. Each agent is localized in a limited region as its mobility limited by major switching costs. Hence he is not aware of the effects of its re-location in such a multidimensional space on the viability of the knowledge externalities and interactions. The topology of the network structure of interactions is also likely to be changed. New communication channels are built and the search for external knowledge is intensified. The amount of knowledge externalities and interactions is likely to increase. The amount of knowledge that each firm can now generate with a given amount of resources also increases because of the higher levels of external knowledge available and the lower cots of communication and networking.

The introduction of innovations may engender a chain reaction that stirs the creative variety of an increasing number of other agents and lead to the generalized introduction of new systems – gales- of innovations. In other circumstances, however, momentum can decline and adaptive reactions prevail. Contingent factors may affect the interplay between structural and technological change and tilt the dynamics of positive feedback: growth and change are characterized by discontinuity

The relationship between the structure of the system and the actual emergence of innovation in fact is clearly recursive. The chances of introduction of innovations are indeed influenced by structure of the system as it stands at time t. The structure of the system shapes the amount of knowledge externalities and interactions that engender positive feedbacks and hence the introduction of localized and productivity-enhancing innovations. The localized structure of interactions plays a key role in qualifying and augmenting the creative reaction of firms caught in out-of-equilibrium conditions so as to enable them to actually generate productivity-enhancing innovations. Innovations, together with other conducts, moreover engender structural change and hence influence the characteristics of the structure at time $t+1$. A new structure is determined with effects both on the flows of knowledge externalities and interactions and in the conditions of product and factor markets. The changes in the markets cannot be fully anticipated by firms. In order to cope with then, firms elaborate new strategies that include the introduction of further innovations.

The understanding of this recursive relationship paves the way to grasping the basic elements of the continual and dynamic system of feedback between the conduct and performance of firms, the rate and direction of technological and structural change with a growing awareness of its evolving and historic characteristics.

A recursive loop takes place between: a) the structural conditions of the system, b) the ensuing amount of knowledge externalities and interactions, c) their crucial role in enabling myopic but creative agents, caught in out-of-equilibrium conditions, to generate new technological knowledge and to introduce new localized, productivity enhancing technologies and d) the consequent changes in the structure of the system. When such a recursive loop takes place and exhibits some levels of historic sustainability, the notion of path dependent complexity becomes relevant. The special case of general equilibrium fades as a multiplicity and changing attractors emerge. Market, knowledge and social interactions feed each other and engender a dynamic process. In a system with no strategic interactions, agents are not induced to try and change their technologies. On the other hand it is clear that a system with low-level knowledge interactions is not able to convert the inducement exerted by strategic interactions into the actual introduction of technological innovations. Social interactions on the other hand have a powerful effect in terms of introducing the endogenous dynamics on the demand side.

Innovation is the emergent property of a system where there is a conducive mix of strategic interactions, able to stir the creative response of firms, and knowledge interactions able to implement them with the supply of external knowledge. Innovation is both the result and cause of out-of-equilibrium conditions.

Complex system dynamics, based upon systemic and creative reactions, substitutes adaptive convergence towards a single attractor. Complex system dynamics provides an analytical framework into which much economics of innovation can be usefully encapsulated. On the other hand complex system dynamics makes it possible an important step forward with respect to evolutionary economics as it enables to overcome the embarrassing role of random variation as a source of innovations. Innovations are the deliberate outcome of the intentional and creative action of firms localized in a well-defined context that characterizes both their competencies and their position in a web of social, strategic and knowledge interactions.

The integration of the economics of innovation and specifically of the economics of localized technological change into the frame of the economics of complexity has two important advantages. On the one hand it shows that innovations are the collective and systemic result of the intentional action of a variety of heterogeneous and interacting firms when embedded in proper innovation systems that favor their creative reaction when facing out-of-equilibrium conditions. On the other it provides the economics of complexity with an articulated analysis of the dynamic interactions between intentional decision making at the agent level and the changing characteristics of the system into which economic action takes place.

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