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THE FOUNDATIONS OF THE ECONOMICS OF INNOVATION

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THE FOUNDATIONS OF THE ECONOMICS OF INNOVATION[1]

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ABSTRACT. During the last forty years, economics of innovation has emerged as a distinct area of enquiry at the crossing of the economics of growth, industrial organization, regional economics and the theory of the firm, becoming a well identified area of competence in economics specializing not only in the analysis of the effects of the introduction of new technologies, but also and mainly in understanding technological change as an endogenous process. As the result of the interpretation, elaboration and evolution of different fields of analysis in economic theory, innovation is viewed as a complex, path dependent process characterized by the interdependence and interaction of a variety of heterogeneous agents, able to learn and react creatively with subjective and procedural rationality.

KEY WORDS: KNOWLEDGE, INNOVATION, TECHNOLOGICAL CHANGE, DIFFUSION, PATH DEPENDENCE, COMPLEXITY

1. Introduction

During the last forty years, economics of innovation has emerged as a distinct area of enquiry at the crossing of the economics of growth, industrial organization, regional economics and the theory of the firm, becoming a well identified area of competence in economics specializing not only in the analysis of the effects of the introduction of new technologies, but also and mainly in understanding technological change as an endogenous process.

As the result of the interpretation, elaboration and evolution of different fields of analysis in economic theory, innovation is viewed as a complex, path dependent process characterized by the interdependence and interaction of a variety of heterogeneous agents, able to learn and react creatively with subjective and procedural rationality.

After the discovery of the residual, the traditional assumptions about the exogeneity of technological change proved to be quite embarrassing and pushed economics to provide and elaborate an endogenous explanation: too large is the share of unexplained growth. Neoclassical economics provided an elaborated and sophisticated framework to understand the conditions for static efficiency. In such a context growth and development are the consequences of exogenous changes in the shapes of the utility functions, in the characteristics of the technology and in the actual demographic conditions as well as the supply of natural resources. This theory

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does not address the actual causes of growth and change. It is limited to analyzing the complementary conditions in terms of rates of growth in the supply of labour and savings that make it possible to take advantage of the effects of 'technology push' falling from heaven like manna and for exogenous growth to take place.

The effort to provide an endogenous explanation of technological change has been nurtured by the sequential and yet overlapping articulations and reinterpretations of different approaches that have been progressively built in a process of reconsideration and reappraisal of the dynamic legacies that had stressed the role of endogenous dynamics, but had been left aside by mainstream theorizing.

Four wide-ranging heuristic frameworks can be identified: the classical legacies of Adam Smith and Karl Marx, the Schumpeterian legacy, the Arrovian legacy, and the biological suggestions stimulated by the Marshallian legacy eventually articulated in the evolutionary approaches leading to complexity.

These four approaches have a clear focus. The classical legacies have been especially useful in understanding the contribution of innovation and technological change to economic growth, mainly at the aggregate level. The induced approach to technological change and the role of learning constitute the core contributions of this line of analysis. The Schumpeterian legacy has provided the building stone to enquire the relationships between innovation and competition in the market place with important implications for the theory of the firm and the theory of the markets. The Schumpeterian approach has focused the role of innovation as a competitive tool and of both the corporation and entrepreneurship as the driving factors. The Arrovian legacy has made it possible to explore the economics of knowledge with its powerful implications for the theory of organization and regional economics. Finally, biological grafting stimulated by the Marshallian legacy and evolutionary approaches, lately reinvigorated by complexity thinking, has paved the way to understanding the path dependent dynamics and systemic interdependencies that characterize technological and structural change.

These four approaches have evolved in parallel in the second part of the XX century with a process of specialization and consolidation of their respective areas of expertise. Yet an increasing number of lateral and horizontal contributions have been made feeding a process of increasing convergence and integration. As a result a rich web of overlapping stratifications has been gradually growing.

In order to highlight the origins and the evolution of the economics of innovation, a matrix of analytical tools can be elaborated. The basic line of understanding is found along the diagonal, where each field matches its own basic approach. Much interest, however, is found in cells around the diagonal, where an increasing number of cross contributions can be identified. The result of the process is an increasing complementarity and compatibility among the four approaches into the new frame provided the economics of complexity. Table 1 synthesizes the matrix of notions and concepts elaborated in the economics of innovation and shows how the different analytical trails have contributed the evolution of the field. In so doing Table 1 provides a guide to the entire work.

TABLE 1: THE INNOVATION MATRIX

	INNOVATION AND GROWTH	INNOVATION AND COMPETITION	INNOVATION AND KNOWLEDGE	INNOVATION WITHIN EVOLVING SYSTEMS
THE CLASSICAL LEGACIES	-Division of labor -Demand-Pull -Inducement		-Learning -Collective Knowledge	-Funtional differentiation
THE SCHUMPETERIAN LEGACIES	-Creative destruction	-The Schumpeterian hypothesis. -Entrepreneurship -Monopolistic competition -Structure-Conduct-Performance -Dominant design -Network externalities	-Gales of innovation -R&D -Technology push -Technological opportunities	-Sectoral patterns -Technological regimes -Creative adoption
THE ARROVIAN LEGACY	-Residual -Learning by doing -Learning by using -New growth theory	-Knowledge as a production factor -Knowledge quasi-rents -Spillover	-Knowledge as an economic good -Knowledge spillover -Industrial districts -Knowledge asymmetries -Knowledge governance	-General purpose technologies -Technological systems
THE MARSHALLIAN LEGACY: EVOLUTION AND COMPLEXITY	-Technological trajectories -Technological paths	-Life cycle -Epidemic diffusion -Replicator dynamics	-Localized technological knowledge -Innovation networks -Knowledge as an input and an output -Competence	-Localized technological change -Past dependence -Positive feedbacks -Path dependence -Generative relationships

The four approaches share a basic departure from standard economics: the attribution to economic agents with the capability to change their production and utility functions.

A few common threads emerge across the four approaches. The basic notion of learning is eventually articulated in terms of creative reaction. The context into which learning takes place receives increasing attention. The heterogeneity of learning and interaction conditions emerges a second common thread. The effects of historic time both at the system level and at the agent level is acknowledged. The conduct of each agent is shaped by the effects of the past and yet they are credited with the capability to alter the trajectories of their activities by means of the generation of new technological knowledge and the introduction of technological innovations. The dynamics of feedback is finally appreciated in the different contexts: the introduction of innovations changes the structure of the system and this in turn affects the conduct of agents, including the introduction of other innovations.

The shared understanding of the working of the economic system as a complex dynamic process is possible as soon as the systemic properties that belong to economics as a science, are extended so as to include the possibility for agents and subsystems to internally generate new technological knowledge and hence new production technologies and new preferences. What is more, it is not difficult to do this for most of standard microeconomics can be retained and properly implemented at the agent level: heterogeneous agents do try and optimize within the strong limitations of their subjective conditions. The aggregate outcome of their action however is far from a general equilibrium steady state, but consists rather in a process of continual change.

This view can be considered the result of the integration of the four approaches and of the four fields of investigation into one broader analytical platform provided by complexity economics. With respect to Table 1 we see that, especially at the bottom right of the diagonal, the borders of the cells themselves are more and more blurred as systematic overlapping across fields of investigation and traditions of analysis take place. Economics of innovation emerges as a distinctive field of investigation with a broad array of complementary concepts articulated within convergent and consistent fields of specialization.

The aim of this work is to provide an interpretative framework able to identify the main contributions of the economics of innovation and to track the emergence of the view that 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, 2007)[2].

2. INNOVATION AND GROWTH: THE REAPPRAISAL OF THE CLASSICAL LEGACIES

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[2] Antonelli, C. (2007), *The path dependent complexity of localized technological change: ingredients, governance and processes*, Routledge, London.

2.1 THE DISCOVERY OF THE RESIDUAL

The discovery of the residual coincides with the birth of economics of innovation. In neoclassical economics technological change is exogenous. Occasionally technological shocks perturbate the equilibrium conditions of the system: firms are not supposed to be able to change intentionally their technologies. This section brings together the key steps in the departure from this obsolete position. The empirical investigations of Moses Abramovitz (1956)[3] and Robert Solow (1956)[4] show that over 50% of the growth of output in the US economy between the end of the XIX century and the first part of the XX century cannot be reconciled with the growth of inputs. Technological change should be credited for an astonishing contribution to economic growth. Equilibrium economics is able to explain only a fraction of the economics system. This evidence becomes a challenge.

The basic puzzle remains a problematic core for this area of specialization. How innovations come to the market place, how novelty takes place in our understanding of the economic and technological interplay, how and why total factor productivity grows, how firms and economic agents at large generate and react to the introduction of novelty are the key questions. The birth of economics of innovation as a specific area of enquiry and investigation in the broader context of the increasing specialization of economics, can be considered the ultimate result of the analysis of growth of output and labor productivity, ceteris paribus input levels, when and if increasing returns do not take place.

This section brings together the founding stones of the classical analysis on the endogenous determinants of technological change and the recent approaches elaborated after the discovery of the residual. As a matter of fact the writings of Adam Smith and Karl Marx have provided the key points of departure of the recent approaches to the economics of technical change.

2.2 ADAM SMITH AND THE DEMAND PULL HYPOTHESIS

Adam Smith[5] contributes the basic elements of the demand-pull approach. The division of labor is determined by the extent of the market. All increases in the extent of market can lead to an increase in the division of labor and hence in specialization. Specialization in turn is the base for dedicated learning and the eventual introduction of innovations. Innovations increase the efficiency of labor and hence the extent of the market. As Rosenberg (1965)[6] notes Adam Smith has laid down the foundations for the analysis of technological change as an endogenous and self-feeding process. Allyn

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[3] Abramovitz, M. (1956), Resources and output trends in the US since 1870, *American Economic Review* 46, 5-23.

[4] Solow, R. M. (1957), Technical change and the aggregate production function, *Review of Economics and Statistics* 39, 312-320.

[5] Smith, A. (1776), *An inquiry into the nature and causes of the wealth of nations,* 1776 (The London Edition, 1976).

[6] Rosenberg, N. (1965), Adam Smith on the division of labour: Two views or one, *Economica* 127-139.

Young (1928)[7] and Nicholas Kaldor (1972)[8] have much developed this approach and shown the irrelevance of equilibrium economics when the dynamics of technological change is understood.

Adam Smith provides the most impressive and clear account of the essential role of technological knowledge and technological change as endogenous factors in explaining the dynamic character of the economic process. The first four books of the founding stone of economics are fully devoted to exploring the economic process and its determinants. The very first lines of "An Inquiry into the Nature and Causes of the Wealth of Nations" are devoted to the relationship between productivity and division of labor. According to Adam Smith, the growth in productivity is a consequence of the division of labor: "The greatest improvement in the productive powers of labor, and the greater part of the skills, dexterity, and judgment with which it is any where directed, or applied, seem to have been the effects of the division of labor" (Smith, 1776:13).

The division of labor has a clear causal role in Adam Smith view of the origins of the accumulation of competence and knowledge. More specifically, Adam Smith elaborates a sequence according to which the division of labor is the cause of an increase in competence. The generation of new knowledge builds upon the increase in competence. Technological innovations are the final result of the process. A bottom-up theory of technological knowledge is fully articulated by Adam Smith. Learning by doing and learning by using are at the origin of inventions, which eventually make it possible the introduction of new and improved machineries.

According to Adam Smith the professional competence acquired by means of learning processes and ultimately because of the division of labor is the cause of the skills of workers. Learning by doing and by using processes, internal to each firm, are not the sole factors in the accumulation of new knowledge. An important role is played by the producers of machines and also by scientists. The division of labor in conclusion, enters the working of science and becomes a powerful factor in the organization and efficiency of scientific progress.

The reading of Adam Smith confirms the key role of the economics of knowledge in the understanding of the economic process shaped by continual development based upon the introduction of new technologies. Actually one finds in Adam Smith the early foundations of the economic understanding of the mechanisms at work in the generation of technological knowledge. Adam Smith in fact provides a comprehensive analysis where technological knowledge is regarded as the eventual result of at least three processes: a) a bottom up process by means of learning by doing and learning by using; b) the specialized activity of 'philosophers' in a top-down

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[7] Young, A.A. (1928), Increasing returns and economic progress, *Economic Journal* 38, 527-542.

[8] Kaldor, N.(1972), The irrelevance of equilibrium economics, *Economic Journal* 82, 1237-1255.

process and finally, c) the interactions with suppliers of machinery and intermediary inputs.

Building upon these bases the dynamic engine of Adam Smith is in place. The division of labor is the consequence of the extent of the market and is the cause of the increase of technological knowledge, hence of inventions and eventually technological innovations. Technological innovations in turn lead to the increase in productivity. The increase in productivity leads to the increase in the demand and hence of the extent of the market. The analysis of Adam Smith comes to full circle.

Alfred Marshall follows the line of enquiry elaborated by Adam Smith and acknowledges the dual relationship between the division of labor and the introduction of new technologies. Technological change and specialization are two sides of the same process. Allyn Young is probably the author who, following Marshall, has contributed more to focus attention on the key role of endogenous dynamics in the work of Adam Smith. According to Allyn Young the interaction between technological and structural change fed by the dynamics of division of labor- specialization- accumulation of competence- introduction of new technologies and further increase in the extent of the market is change is progressive and cumulative. In so doing Young stresses the critical role of technological change, as both the product and the cause of increasing functional differentiation and complementarity within economic system, in economic growth. Young lays down the first elements of a system dynamic approach to understanding economic growth. Economic systems in fact are viewed as complex and dynamic adaptive organizations composed by autonomous and yet interrelated and interdependent units that change over time.

Nicholas Kaldor digs even deeper and fully recognizes the essential contribution of Adam Smith to building a dynamic theory of the economic process where technological change and technological knowledge pulled by the interplay between the beneficial effects of the division of labor and the extent of the market are at the center of the stage. Cumulative technological change takes place, in out-of-equilibrium conditions, in an economic system where and when firms are not viewed as passive users of given technologies, only able to select the techniques more appropriate to a given set of relative prices, but as agents able to change and generate their own technologies.

Building upon Adam Smith, Jacob Schmookler (1954)[9] provides empirical support to the hypothesis that demand growth pulls the increase of technological knowledge, hence of inventions and eventually technological innovations. Nathan Rosenberg and David Mowery (1979)[10] provide an outstanding account of the pervasive role of the demand-pull hypothesis within the post-Keynesian approach.

2.3 KARL MARX AND INDUCED TECHNOLOGICAL CHANGE

[9] Schmookler, J. (1954), The level of inventive activity, *Review of Economics and Statistics* 36, 183-190

[10] Mowery, D. and Rosenberg, N. (1979), The influence of market demand upon innovation: A critical review of some recent empirical studies, *Research Policy*

Karl Marx[11] contributes the first elements of a theory of endogenous technological change as the result of the intentional process of augmented labor substitution. When wages increase, capitalists are induced to introduce new capital-intensive technologies that help reducing the pressure of unions and increase the total efficiency of labor.

The analysis of technological change plays a key role in the work of Karl Marx. Technological change in fact is the basic tool by means of which capitalists increase profits together with the extraction of surplus value from the production process. Karl Marx stresses the dual role of technological change. On the one hand technological change makes it possible to reduce the price of goods in the market place. On the other, technological change makes it possible to increase the extraction of surplus value (Rosenberg, 1976)[12]. The competitive process among capitalists feeds the former. The exploitation of labor by capitalists as a class is the ultimate result of the latter (Rosenberg, 1992)[13].

The relationship between the levels of wages and the actual profitability of introduction and adoption of the new machines is so clear and direct that Marx can understand the relative differences in the profitability of adoption of the same machine in different countries, characterized by different relative factor costs. The increase in the profitability of each firm is the direct incentive to the action of each capitalist introduction of technological innovation embodied in new machines. Its introduction at the system level has the direct effect of substituting capital to labor. The competitive pressure of the capitalists however fuels the dynamics of the process. The decline of the number of workers is relative, but not absolute. The inducement hypothesis is set forth and will characterize much of the economics of innovation (Rosenberg, 1969)[14].

Specifically a distinction has to be made between models of induced technological change, which focus the changes in factors prices, and models of induced technological change, which stress the static conditions of factors markets. In the first approach, following Hicks and Marx, firms are induced to change their technology when the price of a production factor increase (Hicks, 1932)[15]. According to John Hicks the change in factor prices acts as a powerful inducement mechanism, which explains both the rate and the direction of introduction of new technologies. The

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[11] Marx, K. (1867, 1976), *Capital. A critique of political economy*, Penguin Books, Harmondsworth.

Marx, K. (1857-58), *Grundrisse* (Economic manuscripts of 1857-58, First Version of The Capital)

[12] Rosenberg, N. (1976), Marx as a student of technology, *Monthly Review* 28, 56-77.

[13] Rosenberg, N. (1992), Economic experiments, *Industrial and Corporate Change* 1.

[14] Rosenberg, N. (1969). The direction of technological change: Inducement mechanisms and focusing devices*, Economic Development and Cultural Change 1-24*

[15] Hicks, J.R. (1932), *The theory of wages*, Macmillan, London.

change in factors prices in fact induces firms to introduce new technologies, specifically directed to save on the factor, which has become more expensive. The introduction of new technologies complements the standard substitution process, i.e. the technical change consisting in the selection of new techniques, defined in terms of factor intensities, on the existing isoquants. In this case technological change is considered an augmented form of substitution: technological change complements technical change (Fellner, 1961)[16].

This approach to the induced technological change differs from the static Kennedy-von Weiszacker-Samuelson approach, according to which firms introduce new technologies in order to save on the production factors that are relatively more expensive. In this second approach the levels of factor price matter instead of the rates of change. This approach has shown a major limitation of the former. From simple algebraic calculation it is in fact clear that firms have an incentive to introduce labor-intensive technologies, in labor abundant and capital scarce regions and countries, even after an increase in wages. The Kennedy-von Weiszacker-Samuelson approach however is severely limited from the dynamic viewpoint. It is no longer clear when and why firms should innovate. Consistently only the direction of technological change can be induced, rather than the rate. Both approaches, as it is well known, have been often criticized using the Salter's argument, according to which firms should be equally eager to introduce any kind of technological change, either labor or capital intensive, provided it makes it possible to reduce production costs and increase efficiency (Binswanger and Ruttan, 1978)[17].

It is interesting to note that the analysis of the role of relative factor endowments in explaining the direction of technological change has been recently revived to explain the bias of new information and communication technologies in terms of skill intensity. Most recently the debate on the so-called 'biased technological change' has further elaborated this approach (Acemoglou, 1998)[18].

2.4 LEARNING AS THE ENGINE OF GROWTH

The first attempt to deal with the residual in the neoclassical framework is provided by Kenneth Arrow with the notion of learning. Kenneth Arrow (1962 a)[19] lays down the foundations for a theory of economic growth based upon learning processes that

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16 Fellner, W. (1961), Two propositions in the theory of induced innovation, *Economic Journal* 71, 305-308.

17 Binswanger, H.P. and Ruttan, V.W., (eds.), (1978), *Induced innovation*: *Technology institutions and development*, Johns Hopkins University Press, Baltimore (pp.13-43).

18 Acemoglu, D. (1998), Why do new technologies complement skills? Directed technical change and wage inequality, *Quarterly Journal of Economics* 113, 1055-1089.

19 Arrow, K. J. (1962), The economic implications of learning by doing, *Review of Economic Studies* 29, 155-173.

make it possible the generation of new knowledge and eventually the introduction of new technologies. Agents, as well as firms, are now credited with the capability to learn. Learning is the result of repeated actions over time and reflective thinking. Learning has strong cumulative features and as such leads to dynamic increasing returns where cost reduction is associated with time rather than sheer size of production.

This approach has a strong limitation as it is consistent with the orthodoxy only as long as it applies to the representative agent: learning should be ubiquitous and symmetric across agents in the system. The evidence, on the opposite, shows that the distribution of the residual is highly uneven across regions, industries, firms and especially along historic phases. Nevertheless, the rediscovery of the notion of learning, originally introduced by Adam Smith, is especially fertile, in many different directions. Atkinson and Stiglitz (1969)[20] develop the analysis of learning and appreciate the role of the technical constraints in shaping the process: learning is possible only in the limited spectrum of techniques where firms have been practicing. Hence technological change is localized.

2.5 THE NEW GROWTH THEORY

The theory of learning provides the basis for important efforts to integrate the analysis of technological change into an equilibrium context of analysis: the new growth theory. The new growth theory builds upon three important acquisitions of economics of knowledge: a) the distinction between generic and tacit knowledge, and the related notion of technological knowledge as a quasi-public good because of quasi-appropriability; b) the understanding of technological externalities and the dynamics of spillover, and c) the notion of monopolistic competition as a result of the introduction of new products.

According to Romer (1994)[21] economic growth relies upon the collective access to generic knowledge, which flows in the air. Romer distinguishes between generic technological knowledge, germane to a variety of uses and specific technological knowledge embodied in products and as such with strong idiosyncratic features. Specific knowledge can be appropriated; generic knowledge instead retains the typical features of the Arrovian public good. Innovators generate generic knowledge while are engaged in the introduction of new specific knowledge embodied in new products and new processes. The production of specific knowledge takes advantage of the collective availability of generic one. The spillover of generic knowledge helps the generation of new specific knowledge by third parties and yet does not reduce the incentives to the generation of new knowledge for the strong appropriability of the specific applications.

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20 Atkinson, A.B. and Stiglitz, J.E. (1969), A new view of technological change, *Economic Journal* 79, 573-578.

21 Romer, P.M. (1994), The origins of endogenous growth, *Journal of Economic Perspectives* 8, 3-22.

The new growth theory has been further enriched with the grafting of the Schumpeterian rivalry with the notion of creative destruction elaborated by Aghion and Howith (1992)[22]. Monopolistic competition characterizes the markets for products and provides a coherent context for a close variety of products, drawing from the same pool of generic knowledge, to coexist.

The new growth theory has been able to adopt and adapt much progress put forward by the economics of innovation and yet to miss the core of the analysis: the evolutionary outcome of the interaction between the introduction of new technologies and the changes brought about in the economic system. Innovation is but a part of a broader process of interaction between the effects and the determinants of technological and structural change, which takes place in a disequilibrium context.

2.6 TECHNOLOGICAL PATHS AND GENERAL PURPOSE TECHNOLOGIES

The long-term analysis of economic growth shows the persistency of factor intensity presumably explained by elastic barriers based upon local irreversibilities and switching costs that prevent firms to adjusting to the changing levels of relative input costs. On the opposite, when significant changes in the relative costs of production factors take place firms react with the introduction of new technologies. The path breaking analysis of Paul David (1975)[23] lays down the foundations of much of contemporary economics of technological change intertwined with the historic analysis of structural change.

The Schumpeterian notion of innovation as the basic competitive tool enables Nelson and Winter (1975)[24] to mimic with simulation techniques the working of a system where myopic firms follow innovative routines in order to compete beyond maximization rules along technological trajectories and in so doing generate growth.

The notion of general purpose technology introduced by Breshanan and Trajtenberg (1995)[25] and further elaborated by Lypsey, Bekar and Carlaw (1998)[26], stresses the

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22 Aghion, P. and Howitt, P. (1992), A model of growth through creative destruction, *Econometrica* 60, 323-51.

23 David, P.A. (1975), *Technical choice innovation and economic growth,* Cambridge University Press, Cambridge.

24 Nelson, R.R., Winter, S.G. (1975), Growth theory from an evolutionary perspective. The differential productivity puzzle, *American Economic Review* 65, 338-44.

25 Bresnahan, T. F., Traitenberg, M. (1995), General purpose technologies: ‘Engines of growth’? *Journal of Econometrics* 65, 83-108.

26 Lypsey, R., Bekar, C. and Carlaw, K. (1998), General purpose technologies: What requires explanation, in Helpman, E. (ed.) *General purpose technologies and economic growth*, The MIT Press, Cambridge.

systemic character of technological change. New general purpose technologies, are the result of the complementarity and interdependence of a variety of technological innovations being sequentially introduced and are characterized by high levels of fungibility as they apply to a great variety of production processes.

The analysis of the role of the structural characteristics of economic systems at large and specifically of the role of the structure of relative prices, as determined by the endowment of basic inputs and of the dynamics of industries and sectors as factors shaping the rate and direction of technological change provides a historical context into which the analysis of the interplay between technological and structural change makes a step forward (Wright, 1997)[27]. Developing the localized technological change approach, Antonelli (2006)[28] argues that because there are irreversibilities, limited knowledge and local learning, the introduction of new technologies is induced by the disequilibrium conditions brought about in each system by all changes in relative factor prices. The direction of technological change in terms of its specific form of bias and how it is introduced and adopted, however, reflects the specific conditions of local factor markets. Well-defined long-term technological paths emerge in each region and they depend on the selection process in product markets. The more rigid and idiosyncratic, the endowment of production factors and the system of relative prices are, the more specific the technological path of each region is likely to be.

The analysis of the asymmetric effects of the introduction and diffusion of new technologies and of the structural determinants of the rate and the direction of technological change enables Paul David (2000)[29] to elaborate the analysis of the role of the path dependent interplay between structural and technological change. Technological change is now viewed as a process able to change the characteristics of the system and yet itself the product of the characteristics of the system at each point in time. The application of the new general purpose information and communication technology in the US does not materialize in terms of productivity, and is better understood in terms of system transition.

3. INNOVATION AND COMPETITION: THE SCHUMPETERIAN LEGACY

3.1 INTRODUCTION

Innovation, as distinct from invention, is the distinctive feature of the competitive process. Competition takes place by means of the introduction, adoption and diffusion

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27 Wright, G. (1997), Toward an historical approach to technological change, *Economic Journal* 107, 1560-1566.

28 Antonelli, C. (2006) Localized technological change and factor markets: Constraints and inducements to innovation, *Structural Change and Economic Dynamics* 17, 224-247

29 David, P. A., (2000), Understanding digital technology's evolution and the path of measured productivity growth: Present and future in the mirror of the past, in Brynolfsson, E., Kahin, B., (eds.), *Understanding the digital economy*, MIT Press, Cambridge MA, pp. 49-95.

of innovation, rather than by means of quantity and price adjustments. At the same time competition is the driving engine that pushes firms to introduce innovations.

The work of Joseph Schumpeter is at the heart of economics of innovation (Rosenberg, 1994)[30]. The definition of innovation, the distinction between innovation, invention and diffusion, the understanding of the concentration of innovation in time and space with the notion of gales of innovations, the analysis of the key role of the corporation as the appropriate institution for fostering the rate of introduction of innovations are all based upon the contributions of Schumpeter from 'The Theory of Economic Development' his first book (1912 and 1934)[31] to 'The instability of capitalism' the key journal article of 1928, to 'Business Cycles' (1939) and finally 'Capitalism, Socialism and Democracy'(1942)[32].

Every student of economics of innovation is aware of the path breaking contribution of Joseph Schumpeter to the economics of innovation and technological change. An extensive and comprehensive analysis of his many contributions to this approach would risk to be easily repetitive. Much attention has been called upon the evolution of the thinking of Schumpeter upon the role of technological change in economic development. A divide between the 'first' and the 'second' Schumpeter has been identified. The first Schumpeter, that is tradition based upon the "Theorie der Wirtschaflichen Entwicklung'' originally published in German in 1912 pays attention to entrepreneurship as the driving mechanism. Entrepreneurs that create new firms to enter the markets would primarily introduce technological innovations. The key role attributed to entrepreneurship has raised some problems about the endogeneity of innovation. The second Schumpeter is based upon the 1942 book 'Capitalism, Socialism and Democracy' where the driving role of the large corporation as the engine for the introduction of innovations is highlighted. The well-known Schumpeterian hypothesis is based on this second book: the monopolistic power and the large size of corporations favor the allocation of resources and the matching of competences to generating new technologies. A divide between static and dynamic efficiency arises: static inefficiency, stemming from monopolistic power, is compensated by dynamic efficiency, stemming from faster rates of introduction of new superior technologies. The second Schumpeter however expresses also some concern about he long-term viability of the competitive mechanisms based upon innovations, because of the increasing routinization of the activities leading to the

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30 Rosenberg, N. (1994), *Exploring the black box*, Cambridge University Press, Cambridge, (Chapter 2, Joseph Schumpeter: Radical Economist: pp. 47-61).

31 Schumpeter, J.A. (1912, 1934), *The theory of economic development*, Harvard University Press, Cambridge.

32 Schumpeter, J.A. (1928), The instability of capitalism, *Economic Journal* 38, 361-386.

Schumpeter, J.A. (1939), *Business cycles*, McGraw-Hill, New York.

Schumpeter, J.A. (1942), *Capitalism, socialism and democracy*, Harper and Brothers, New York.

introduction of innovations within the large corporation. Innovation here is fully endogenous, but 'routinized'.

In the "Instability of capitalism" published in The Economic Journal in 1928 however the 'two Schumpeters' are well integrated and coexist consistently. It seems appropriate to pay more attention to this contribution. Here in fact the theoretical distance between the dynamic analysis of the economic process, based upon the understanding of the central role of technological change in the market competition and the Walrasian analysis of the general equilibrium is especially clear. Innovation, as distinct from invention, is not only endogenous but the intrinsic element of the capitalistic economy. Innovation cannot be regarded as an external economy, because this is the distinctive feature of the competitive process.

The Schumpeterian approach to innovation as an essential component of the competitive process is well consistent with the Marshallian interpretation of the competitive process. Variety and selection are essential elements of the Marshallian notion of competition. Firms, diverse in terms of size, location and efficiency, confront each other in the product market place and are sorted out by the working of the competitive process. Entry and exit feed the dynamics of the process. In this context each firm is confronted with a continual redefinition of its relative market context and has to face the competitive threat brought about by firms that are able to produce at lower costs either because of the access to cheaper production factors or more effective production technologies. In the Marshallian competition, the duration of the adjustment process to an eventual equilibrium is endless and firms experience prolonged out-of-equilibrium conditions in which they can earn transient and yet heterogeneous levels of profits.

The Schumpeterian legacy has been especially fertile in articulating the key relationship between rivalry and intentional innovation and has made it possible to explore the causal relations between barriers to entry, levels of markups, market structure and the incentives to introduce new technologies (Scherer, 1965)[33].

3.2 INNOVATION AND THE CORPORATION

The so-called Schumpeterian hypothesis sketched in *Capitalism socialism and democracy* articulates the hypothesis that large firms are necessary for high rates of technological advance to take place. Barriers to entry and monopolistic competition provide to corporations ex-ante appropriability, reducing the risks of leakage and imitation. In turn large price-cost margins and competence provide corporations with the opportunity to match internal financial resources with dedicated information and competent decision-making so as to fund new promising research activities. In this literature, the large firm takes on a central role and appears the locus of accumulation of sticky technical knowledge and hence technological progress. The funding and the

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[33] Scherer, F.M. (1967), Research and development resource allocation under rivalry, *Quarterly Journal of Economics* 385-389.

performance of research and development (R&D) activities become an integral part of the conduct of large corporations (Nelson, 1959)[34].

3.3 INNOVATION AND MARKET STRUCTURE

Mike Scherer implements the framework structure-conduct-performance, drawn from industrial organization, with the sectoral analysis of technological opportunities – defined as the opportunity to introduce technological innovations impinging upon exogenous scientific breakthrough- as a relevant aspect of the industrial structure and innovation as one of the main conducts of firms. The enriched structure-conduct-performance framework has made it possible to gather a large empirical evidence able to confirm that the size distribution of firms, the levels of concentration and the forms of competition among firms do affect the rates of introduction of innovations and their characteristics. The rich survey by Kamien and Schwartz (1973)[35] provides a detailed review of this literature.

Oligopolistic rivalry provides a framework to understand the 'equilibrium' amount of research and development expenditures but fails both to understand how research translates into innovation and consequently how total factor productivity grows (Dasgupta and Stiglitz, 1980)[36].

The time patterns of entry of firms and hence the evolution of industrial demography, concentration, profitability, and rates of growth of both firms and industries is analyzed within the Schumpeterian sequence of early monopolistic power followed by imitative entry and finally competition. Diffusion matters both on the demand and the supply side.

The new notion of equilibrium-diffusion contrasts the epidemic approach. New technologies are adopted only if and when they fit specific product and factor markets conditions: some agents will never adopt a new technology and the identification of the determinants of the non-adoption becomes relevant. Adopters are no longer viewed as passive and reluctant perspective users, but rather as ingenious screeners that assess the scope for complementarity and cumulability of each new technology with their own specific needs and contexts of action. Profitability of adoption is the result of a process rather than a given fact (Stoneman and Ireland, 1983; Karshenas and Stoneman, 1995)[37].

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[34] Nelson, R.R. (1959), The simple economics of basic scientific research, *Journal of Political Economy* 67, 297-306.

[35] Kamien, M.I., Schwartz, N.L. (1975), Market structure and innovation, *Journal of Economic Literature* 1-37.

[36]Dasgupta, P. and Stiglitz, J.E. (1980), Industrial structure and the nature of innovative activity, *Economic Journal* 90, 266-293.

[37] Stoneman, P. and Ireland, N. (1983) The role of supply factors in the diffusion of new process technology, *Economic Journal* 93, 65-77.

New technologies are adopted only if and when they fit specific product and factor markets conditions: some agents will never adopt a new technology and the identification of the determinants of the non-adoption becomes relevant (Geroski, 2001)[38].

A technology diffuses when it applies to a variety of diverse conditions of use. The intrinsic heterogeneity of agents applies in fact not only to their own technological base but also to the product and factor markets in which they operate. The vintage structure of their fixed costs and both tangible and intangible capital can be portrayed as major factors of differentiation and identification of the specific context of action both with respect to technological change and market strategy (David, 1990)[39].

The flow of investments is determinant to assess the rates of adoption: firms and countries with low investment rates has lower chances to adopt new capital goods. Lower levels of penetration of new capital goods reduce the competitive edge of firms and hence their rates of growth, hence of their rates of investments. Low investment rates in turn are determined by low rates of diffusion: self-feeding processes are likely to take place (Antonelli, 1993)[40]. In this case typical positive feedback occurs: fast rates of investments favor the diffusion of innovations that feed faster rates of growth and hence higher rates of investments. The economics of complexity sneaks in.

Important changes in the profitability of adoption may take place on the demand side because of the effect of network externalities, i.e. the preference of consumers towards a new good is influenced by the number of adopters (Katz and Shapiro, 1986)[41].

Within the context of the economics of localized technological change, the distinction between innovation and diffusion is blurred: adoption is viewed as a complementary component of a broader process of adjusting the technology when unexpected events in the product and factor markets push firms towards a creative reaction. When the

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Karshenas, M., Stoneman, P. (1995) *Technological Diffusion,* in Stoneman, P. (ed.) *Handbook of the economics of Innovation and technological change*, Oxford: Blackwell

38 Geroski, P. (2001), Models of technology diffusion, *Research Policy* 29, 603-625.

39 David, P.A. (1990), The dynamo and the computer: A historical perspective on the productivity paradox, *American Economic Review* (P&P) 80, 355-61.

40 Antonelli, C. (1993), Investment and adoption in advanced telecommunications, *Journal of Economic Behavior and Organization* 17, 227-246.

41 Katz, M.L., Shapiro, C. (1986), Technology adoption in the presence of network externalities, *Journal of Political Economy* 94, 822-841.

stock of adoptions exerts a suitable combined effect both on the gross profitability of adoption and on the costs of adoption, such that the net profitability of adoption and hence the rates of new adoption follow a quadratic path, the dynamics of creative adoption can engender a s-shaped diffusion process (Antonelli, 2006)[42].

An important shift is made when, next to the traditional sequence between the transient monopolistic power stemming from the introduction of an innovation, eventually followed by a few imitators leading to oligopoly and monopolistic competition, an alternative route has been identified with the notion of dominant design. After the introduction of a variety of rival technologies by many rival firms, a selection process takes place and a few leading firms, able to elaborate the dominant design emerge out of the competition with a consistent competitive advantage. Monopolistic rents emerge at the end of the selection process and may last. The diffusion of a new technology is no longer seen as the outcome of the adaptive adoption of a new single technology, but rather of the choice of one new technology among many. Diffusion is the result of the selection of a dominant design out of an original variety of different technological options. New ideas can be implemented and incrementally enriched, so as to become eventually profitable innovations, only when appropriate coalitions of heterogeneous firms are formed both on the demand and the supply side (Abernathy and Clark, 1985)[43].

Pavitt (1984)[44] elaborates a fruitful framework to accommodate and operationalize the variety of paths of technological change across sectors and technologies. In so doing Pavitt implements the neo-schumpeterian approach "structure-conduct-performance" elaborated by Scherer and paves the way to the notion of 'technological regimes' elaborated by Franco Malerba and Luigi Orsenigo[45] that expands the notion of industrial structure so as to include the characteristics of knowledge in terms of appropriability and cumulability. Similar efforts are made by Steven Klepper to update the notion of product cycle and include the rates of entry and exit and the critical phases of industrial shake-out that follow the introduction of an innovation. Incumbent innovators can take advantage of previous innovations in many ways: early competitive advantage makes it possible to fund new research; competence and technological knowledge acquired are useful inputs for further innovations; barriers to entry based upon market shares and size delay imitation;

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42 Antonelli, C. (2006), Diffusion as a process of creative adoption, *Journal of Technology Transfer* 31, 211-226.

43 Abernathy, W.J. and Clark, K.B. (1985), Mapping the winds of creative destruction, *Research Policy* 14, 3-22.

44 Pavitt, K. (1984), Sectoral patterns of technical change: Towards a taxonomy and a theory, *Research Policy* 13, 343-373.

45 Malerba, F., Orsenigo, L. (1996), Schumpeterian patterns of innovation, *Cambridge Journal of Economics* 19, 47-65.

technological advance feeds diversification and entry in new industries (Klepper and Graddy, 1990)[46].

Technological choices concerning the introduction of product and process innovations, the adoption of new technologies provided by suppliers and the imitation of competitors is mingled with market strategies such as specialization, outsourcing, diversification, entry and exit, merger and acquisitions and internal growth. In a continual trial in the market place firms experiment their changing mix of technological and market conduct. At the aggregate level the result is the market selection of new better technologies, often characterized by strong systemic complementarities. The changing coalitions between different groups of players in overlapping and yet specific technological arenas shape the rate and direction of technological change at large In this context the shake-out of the system may favor the emergence of new industrial architectures where firms and technologies find a new contextual location (Henderson and Clark, 1990)[47].

3.4 INNOVATION AND ENTREPRENEURSHIP

Following Schumpeter Mark 1 - the literature inspired by *The Theory of Economic Development* - the supply of entrepreneurs able to spot new technological opportunities and to understand the possible technological and economic applications of new scientific breakthrough is considered an important factor to understand the pace of introduction of new technologies and their specific economic and technological characteristics. This approach praises the role of new firms as vectors of new technologies and suggests that only high birth levels of new firms can sustain the rates of technological change. Large empirical evidence has been provided to support the hypothesis (Acs and Audretsch, 1988)[48].

The analysis of the institutional and economic conditions, which favor entrepreneurship, and the entry of new innovative firms in the market place at large, becomes an important area of investigation. Entrepreneurship in this context supplies evidence to the key role of meta-economic factors in assessing the rate and direction of technological change.

Baumol (2004)[49] has recently contributed this line of enquiry highlighting the role of the social organization of economic, institutional and social mechanisms of

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46 Klepper, S. and Graddy, E. (1990), The evolution of new industries and the determinants of market structure, *Rand Journal of Economics* 21, 27-44.

47 Henderson, R.M., Clark, K.B. (1990), Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms, *Administrative Science Quarterly* 35, 9-30.

48 Acs, Z.J., Audretsch, D.B. (1988), Innovation in large and small firms: An empirical analysis, *American Economic Review* 78, 678-690.

49 Baumol, W.J. (2004), Entrepreneurial enterprises, large established firms and other components of the free-market growth machine, *Small Business Economics* 23, 9-21

identification and valorization of the 'given' supply of creative talents distributed at random in any economic system. The larger the number of creative talents each system is able to identify and valorize and the larger is the dynamics of growth in output and efficiency in the economic system. Here creative talents are an exogenous characteristic distributed at random, but the filtering mechanisms elaborated within the economic system are endogenous.

4. INNOVATION AND KNOWLEDGE: THE ARROVIAN LEGACY

4.1 KNOWLEDGE AS A PRODUCTION FACTOR

The economics of knowledge owes much to the classical legacy of Karl Marx, as Nathan Rosenberg (1974)[50] recalls. The systematic application of scientific knowledge to the production process becomes, in Marx, the distinctive feature of capitalism. First the collective character of technological knowledge is clearly grasped. Technological knowledge consists in a complex system of machines, skills and workers all characterized by distinctive elements of complementarity, interoperability and necessary compatibility. Second, technological and scientific knowledge are characterized by the strong elements of non-exhaustibility and limited appropriability. Their application however requires dedicated competence and resources, which have a strong idiosyncratic character. In order to keep the process in motion, technological knowledge is constantly reproduced and expanded.

In the Grundrisse the analysis of Marx of the central role of science in the capitalist process fetches extraordinary levels of clarity and insight. Technological change is fully endogenous to the economic system. More specifically Marx argues that the levels of endogeneity of technological change are themselves an indicator of the advance of an economic system. The notion of knowledge as an endogenous productive force is clearly identified by Marx. Actually the levels of endogeneity of knowledge, as a distributed economic force shared by a myriad of agents, fed by the combination of learning processes that lead to the accumulation of competence and tacit knowledge with scientific processes of deduction, and transformed into a mean of accumulation of capital pushed by profit maximization (the general intellect), become a measure of the advance of capitalism as a social system.

Alfred Marshall[51] further elaborates the dynamic approach along the lines of the analysis paved by Marx, and Adam Smith and makes explicit that knowledge is a key component of capital and itself a production factor. Second, Alfred Marshall identifies the collective character of technological knowledge as a process where a variety of agents, co localized within the industrial districts, contribute complementary bits of knowledge. Knowledge externalities play a key role in providing firms essential inputs for the generation of new knowledge.

Finally, Alfred Marshall accommodates, within competitive markets, the heterogeneity of firms and explains it in terms of the different levels of knowledge

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[50] Rosenberg, N. (1974), Karl Marx and the economic role of science, *Journal of Political Economy* 82

[51] Marshall, A. (1890*), Principles of economics*, Macmillan, London (1920:8th Edition).

and competence possessed by each firm. Quasi rents are the direct remuneration of the stock of knowledge and competence that each firm has been able to accumulate and valorize.

4.2 KNOWLEDGE AS AN ECONOMIC GOOD

Building upon these foundations Kenneth Arrow (1962)[52] makes an important step forward focusing the analysis of knowledge as an economic good per se, no longer embedded either in capital products or organizations. Until then, knowledge was not regarded as a separate item. The analysis of knowledge as an economic good made it possible to grasp the causes of the radical failure of the market place to perform its traditionally functions and the ensuing severe risks of under-production of knowledge in market systems.

The results of the new approach are path breaking: i) knowledge is the basic intermediary input for the increase of efficiency; ii) the incentive, in terms of social desirability to the production of knowledge is huge: any economic system would dedicate most of its resources to the generation of new knowledge as a way to increase the efficiency in the production of all the other goods; however, iii) because of the major limitations of knowledge as an economic good in terms of non-appropriability, non-excludability, non-rivalry in use, non-exhaustibility and non-divisibility, the private profitability of knowledge generating activities is well below social desirability; moreover iv) because of the high levels of uncertainty both in generation and appropriation, economic systems are unable to fund the correct amount of resources to the generation of new knowledge and hence to increase the production of goods via the increase in the general efficiency of the production process. Hence v) dynamic inefficiency adds to static one**:** the markets for knowledge, as a stand-alone good, are inefficient and hence the necessary levels of division of labor and specialization cannot be achieved. A radical market failure is the direct consequence of the characteristics of knowledge, as an economic, private, and unbundled good. The failure of markets for knowledge is twofold: it takes place both in the markets for knowledge as an output, and in the markets for financial resources necessary to undertake its generation.

The attribution to scientific knowledge of the characteristics of a public good sanctions, and legitimates, a division of labor between firms and universities. The latter are responsible for the production and distribution of this public good. Firms are expected to be able to collect and implement the stimulus, which was set off by new scientific discoveries. The State's role in this situation was that of an indispensable intermediary, which collected the taxes necessary to finance university research. Scientific inventions perfected and improved in an academic ambient, and therefore, meta-economics, produce effects in terms of technological opportunities (Dasgupta and David, 1994)[53].

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52 Arrow, K. J. (1962), Economic welfare and the allocation of resources for invention, in Nelson, R. R. (ed.) *The rate and direction of inventive activity: Economic and social factors,* Princeton University Press for N.B.E.R., Princeton.

53 Dasgupta, P., David, P. A. (1994), Towards a new economics of science, Research Policy 23, 487-521.

Griliches and Pakes (1980)[54] confirm empirically, at the firm level, that technological knowledge, as measured by patent statistics, can be considered an output in a knowledge production function where R&D activities are the main inputs.

The appreciation of other relevant inputs in the knowledge production function, such as external knowledge that can be used in the production of new knowledge, leads to the revival of the Marshallian analysis of externalities with the identification of knowledge spillovers. Regional economics contribute the analysis of spillovers with substantial understanding about the role of geographic proximity in favoring the access to external knowledge with positive effects upon the productivity of resources invested internally in research and development expenditures (Jaffe, 1986; Griliches, 1992; Audretsch and Feldman, 1996)[55].

The Arrovian view of knowledge as a quasi-public good is contrasted by a radical change in perspective, which stresses the role of learning by doing and learning by using as the basic engine of accumulation of knowledge. New technological knowledge stems from such learning processes and especially from the efforts to convert tacit knowledge into new procedures, which can be shared and transferred (Stiglitz, 1987)[56]. The new bottom-up understanding of the discovery process contrasts the traditional top-down approach to the origin of technological innovations. The analysis of the accumulation of technological knowledge plays a key role in this context. The important role of tacit knowledge, embedded in the organization of innovators and especially in their learning procedures, reduces the capability of perspective imitators to absorb the new knowledge and favors higher levels of appropriability (Malerba, 1992)[57].

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54 Griliches, Z., Pakes, A. (1980), Patents and R&D at the firm level*, Economic Letters* 5, 377-381.

55 Jaffe, A.B. (1986), Technological opportunity and spillover of R&D: Evidence from firms' patents, profits and market value, *American Economic Review* 79, 985-1001.

Griliches, Z. (1992), The search for R&D spillovers, *Scandinavian Journal of Economics* 94, 29-47.

Audretsch, D. B. and Feldman, M. (1996), Spillovers and the geography of innovation and production, *American Economic Review* 86, 630-640.

56 Stiglitz, J.E.(1987): Learning to learn localized learning and technological progress, in Dasgupta,P, et al.(eds), *Economic Policy and Technological Performance*. Cambridge University Press, Cambridge. pp.125-144.

57 Malerba, F. (1992), Learning by firms and incremental technical change, *Economic Journal* 102, 845-859.

In this context Alfred Chandler (1977, 1990)[58] and Edith Penrose (1959)[59] provide the foundations of the resource based theory of the firm with emphasis placed on the characteristics of learning processes, the accumulation of technological knowledge and economic competence and the strategic efforts of firms to exploit their technological advance with the creation and valorization of idiosyncratic production factors (Langlois and Foss, 1999)[60].

4.3 INFORMATION ECONOMICS FOR THE ECONOMICS OF KNOWLEDGE

The distinction introduced by Kenneth Arrow (Arrow, 1969)[61] between information economics and economics of knowledge provides basic guidance to implement the economics of knowledge. An array of tools elaborated by the economics of information – such as agency theory, transaction costs analysis, signaling theory, economics of contracts- is applied successfully to understanding the generation and dissemination and use of knowledge.

The costs of imitation and absorption of external knowledge are gradually identified. Mansfield (Mansfield, Schwartz, Wagner, 1981)[62] explores empirically the notion of knowledge appropriability and introduces the notion of absorption costs eventually stylized by Cohen and Levinthal (1990)[63].

The efficiency of the internal production of knowledge becomes a central issue and the role of external knowledge as a source of inputs and an opportunity for higher levels of division of labor is appreciated (Nelson, 1982)[64].

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58 Chandler, A.D. (1977), *The visible hand: The managerial revolution in American business,* Harvard University press, Cambridge.

Chandler, A.D. (1990), *Scale and scope. The dynamics of industrial capitalism,* The Belknap press of Harvard University Press, Cambridge.

59 Penrose, E. (1959), *The theory of the growth of the firm*, Oxford University Press, Oxford.

60 Langlois, R.N., Foss, N. J., (1999), Capabilities and governance: The rebirth of production in the theory of economic organization, *Kyklos* 52, 201-18.

61 Arrow, K. J. (1969), Classificatory notes on the production and transmission of technical knowledge*, American Economic Review* 59, 29-35.

62 Mansfield, E., Schwartz, M., and Wagner, S. (1981), Imitation costs and patents: An empirical study, *Economic Journal* 91, 907-918.

63 Cohen, W.M., Levinthal, D.A. (1990), Absorptive capacity: A new perspective on learning and innovation, *Administrative Science Quarterly* 35, 128-152.

64 Nelson, R.R. (1982), The role of knowledge in R&D efficiency, *Quarterly Journal of Economics* 97, 453-470.

In this second step the debate shifts towards the basic issue of the intrinsic complementarity and interdependence, at the technological, industrial and regional levels among the agents in the accumulation of new technological knowledge and economic competence and subsequently in the introduction and adoption of new technologies. Now knowledge is viewed both as the output of a specific research and learning process, and as the input for other activities leading to the generation of new knowledge. Here again the dynamics of positive feedback is at work: the output of one part of the system is the input for another and yet such interactions are mediated by the price mechanism only to a limited extent: complexity economics is again closer.

The Hayekian notion of knowledge as dispersed and fragmented in a myriad of economic agents provides the foundations to the new understanding (Hayek, 1945)[65]. 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. The results of the empirical analyses of Lundvall (1985)[66] and Von Hippel (1976)[67] on the key role of user-producers interactions as basic engines for the accumulation of new technological knowledge and the eventual introduction of new technologies play a key role at this stage. Technological knowledge is now credited with considerable stickiness (Von Hippel, 1998)[68]

The analysis of transaction, agency and communication costs provides basic guidance to elaborate an integrated framework able to understand the matching between types of knowledge and modes and mechanisms of knowledge governance both in generation and exploitation (Teece, 1986; March 1991)[69].

Knowledge transactions are made possible with the enforcement of appropriate contracts, exchanges of hostages within technological clubs and long term, repeated

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[65] Hayek, F.A. (1945), The use of knowledge in society, *American Economic Review* 35, 519-530.

[66]Lundvall B. (1988), Innovation as an interactive process: From user-producer interaction to the nation system of innovation, in Dosi, G. et al, (eds.), *Technical Change and Economic Theory*. Frances Pinter, London, pp. 349-69.

[67] Von Hippel (1976), The dominant role of users in the scientific instrument innovation process, *Research Policy* 5, 212-239.

[68] Von Hippel, E. (1998), Economies of product development by users: The impact of "sticky" local information, *Management Science* 44, 629-644

[69] Teece, D.J. (1986), Profiting from technological innovation: Implications for integration collaboration licensing and public policy, *Research Policy* 15, 285-305.

March, J.C. (1991), Exploration and exploitation in organizing learning, *Organization Science* 2, 71-87.

interactions (Arora and Gambardella, 2001 and 1994)[70]. Communication costs play a key role in assessing the actual capability of firms to access relevant external knowledge and contribute the emergence of new technological systems (Patrucco, 2005)[71]. Proximity of firms to universities and public research centers at large becomes a major source of access to external knowledge provided some efforts are made in order to absorb the knowledge available in the local knowledge commons (Arundel and Geuna, 2004)[72].

The generation and introduction of technological innovations are now viewed as the result of complex alliances and compromises among heterogeneous groups of agents. Agents are diverse because of the variety of competencies and localized kinds of knowledge they build upon. Alliances are based upon the valorization of weak knowledge indivisibilities and local complementarities among technological different kinds of knowledge. The convergence of the efforts of a variety of innovators, each of which has a specific and yet complementary technological base, can lead to the successful generation of a new technology. Here the Schumpeterian notion of gales of innovations that characterize business cycles revives and reveals its heuristic strength (Schumpeter, 1939).

Once more the dynamics of positive feedback emerges as the key factor. Now, however, it is clear that positive feedback can take place only when an appropriate architecture of network relations is formed. The appreciation of the critical role played by the architecture of network relations marks an important step toward the foray of complexity economics.

The issues of complementarity, weak divisibility and technological interdependence become central to understand the attributes of specific technological, industrial and regional systems articulated in systemic networks of interaction and communication into which the dissemination and access to technological knowledge takes place (Freeman, 1991; Nelson, 1993)[73].

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[70] Arora, A., Fosfuri, A. and Gambardella, A. (2001), *Markets for technology*, MIT Press, Cambridge.

Arora, A. and A. Gambardella (1994), The changing technology of technical change: General and abstract knowledge and the division of innovative labor, *Research Policy* 23, 523-532.

[71] Patrucco, P.P. (2005), The emergence of technology systems: knowledge production and distribution in the case of the Emilian plastics district, *Cambridge Journal of Economics* 29, 37-56.

[72] Arundel, A. and Geuna, A. (2004), Proximity and the use of public science by innovative European firms, *Economics of Innovation and New Technology* 13, 543-558.

[73] Freeman, C. (1991), Networks of innovators: A synthesis of research issues, *Research Policy* 20, 499-514.

The new understanding about the asymmetry between debt and equity in the provision of funds for research activities paves the way to a revolution in financial markets. Equity finance has an important advantage over debt in the provision of funds to innovative undertakings because it can participate into the bottom tail of the highly skewed distribution of positive returns stemming from the generation of new knowledge and the introduction of new technologies. This has important consequences both in terms of reduction of both the risks of credit rationing and the costs of financial resources for research activities. Lenders in fact need to charge high interest rates in order to compensate for the risks of failure and to sort out a large portion of the new research activities to avoid as many ‘lemons’ as possible. Equity investors instead find an equilibrium rate of return at much lower levels because they can participate into the huge profits of a small fraction of the new ventures. The fraction of lemons that equity can support is much larger than that of debt; as a consequence, financial equity by means of venture capital can provide a much larger amount of funding for research activities (Gompers and Lerner, 2001)[74].

The creation of technological platforms centered upon new key technologies by means of the cooperation of rival innovators favors upstream the convergence of technologies, and increases downstream the scope for both the widespread diffusion of applications and the introduction of incremental enrichments. This type of systemic approach to innovation reappraises the relationship between services and manufacturing as complementary activities, and overcomes previous understanding rooted on the divide between the two (Consoli, 2007)[75].

The empirical analyses show that technological knowledge is a highly heterogeneous dynamic process characterized by varying levels of appropriability, tacitness, and indivisibility, which take the forms of cumulability, complexity, fungeability and stickiness. The heterogeneity of knowledge leads to different modes of knowledge governance, articulated in a variety of hybrid forms ranging from coordinated transactions and constructed interactions to quasi-hierarchies can be found between the two unrealistic extremes of pure markets and pure organizations (Antonelli, 2006)[76].

5. THE MARSHALLIAN LEGACY INNOVATION WITHIN EVOLVING SYSTEMS

Nelson, R.R. (ed.) (1993), *National systems of innovation*, Oxford University Press, Oxford.

74 Gompers, P.A., Lerner, J., (2001), The venture capital revolution, *Journal of Economic Perspectives*, 15, 145-168.

75 Consoli, D. (2007), Services and systemic innovation: A cross-sectoral analysis, *Journal of Institutional Economics*, 3

76 Antonelli, C. (2006), The governance of localized knowledge. An information economics approach to the economics of knowledge, *Industry and Innovation* 13, 227-261.

5.1 INTRODUCTION

This section identifies the different analytical trails that converge towards the notion of innovation as an emergent property of a complex evolving system. In this approach innovation is the result of path dependent and collective process that takes place in a localized context, if, when and where a sufficient number of failure-induced, creative reactions are made in a coherent, complementary and consistent way.

This approach is the result of the integration within the new emerging paradigm of complexity of three different strands of analysis: a) the early biological graftings, b) the new epistemology based upon the notions of tacit knowledge, bounded and procedural rationality, c) evolutionary approaches and the economics of complexity.

5.2. BIOLOGICAL GRAFTING

Alfred Marshall was the first to note that biology is the Mecca of economics. As a matter of fact, biology provided important suggestions and stimulation to the early economics of innovation.

Alfred Marshall elaborates the legacy of Adam Smith grasping the dynamic complexity of structural change, as articulated in the interaction between specialization and technological change leading to a growing heterogeneity of firms in a context characterized by variety and complementarity: “The development of the organism, whether social or physical, involves an increasing subdivision of functions between its separate parts on the one hand, and on the other a more intimate connection between them. Each part gets to be less and less self-sufficient, to depend for its wellbeing more and more on other parts, so that any disorder in any part of a highly-developed organism will affect other parts also. This increased subdivision of functions, or "differentiation," as it is called, manifests itself with regard to industry in such forms as the division of labour, and the development of specialized skill, knowledge and machinery: while "integration," that is, a growing intimacy and firmness of the connections between the separate parts of the industrial organism, shows itself in such forms as the increase of security of commercial credit, and of the means and habits of communication by sea and road, by railway and telegraph, by post and printing-press.”(Book VIII, I, § 3 and 4).

A first relevant basket of important research programs favored by biological grafting is the analysis of the delays in the adoption of given technological innovations. The economics of the diffusion of new technologies is conceived as the study of the factors, which account for the distribution over time of the adoption of identifiable successful innovations. A new technology is introduced after a scientific breakthrough and yet it takes time for all perspective users to adopt it. The successful and still widening application of the epidemic methodology emerges in this context. The time distribution of adoptions can be conceived as the result of the spread of the contagious information about the profitability of the new technology. Proximity in geographical, industrial and technical space matters here in that it provides reluctant and skeptic, risk-adverse adopters the opportunity to assess the actual profitability of the new technology and hence to adopt it. The grafting of the epidemic analysis into economics of innovation can take place when contagion is assimilated to the spread of information (Griliches, 1957)[77].

Metcalfe (1981)[78] provides a significant improvement to epidemic diffusion: next to epidemic contagion on the demand side also changes in supply account for the distribution over time of adoptions. In so doing Metcalfe reintroduces the basic laws of standard economics into the epidemic framework and shows the relevance of their dynamic interplay. A sequence of logistic diffusion paths takes place when relevant changes on the supply side affect the spread of the epidemic contagion in new categories of perspective adopters.

The second relevant biological graft into economics of innovation is provided the life cycle metaphor. Ever since the Marshallian forest's trees, the life cycle metaphor has been around in the theory of the firm. A shift takes place when the sequence of birth, adolescence, maturity and obsolescence is applied to framing the steps in the life of a new product instead of a new firm. After introduction, the life of new products is characterized by a number of systematic events. According to the product life cycle approach a consistent pattern can be identified in the typology of innovations being introduced, in the evolution of the demand, in the industrial dynamics and in the characteristics of the growth of the firm.

The life cycle metaphor applies to technological innovations: a) The distinction between major innovations and minor ones is articulated and a sequence is identified between the introduction of a major innovation and the eventual swarm of minor, incremental ones; b) a sequence between product and process innovations is identified. After the introduction of a new product, much research takes place in the effort to improve the production process (Abernathy and Utterback, 1978)[79].

The third important contribution in this context is provided by the systematic application of the tools of analysis of natural selection. The biological notion of the selection process helps grasping the sequential features of industrial dynamics along the trajectory. The application to economics of the replicator, a methodology originally conceived in biology to analyze the dynamics of species, elaborated by Soete and Turner (1984)[80] provides a key tool to operationalize the working of the

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77 Griliches, Z. (1957), Hybrid corn: An exploration in the economics of technological change, *Econometrica* 25, 501-522.

78 Metcalfe, J.S. (1981), Impulse and diffusion in the study of technical change, *Futures* 13, 347-359.

79 Utterback, W.J., Abernathy, J.M. (1975), A dynamic model of product and process innovation, *Omega* 3, 639-656.

80 Soete, L.L. and Turner, R. (1984) Technology diffusion and the rate of technical change, *Economic Journal* 94, 612-23

selection process. Metcalfe (1997)[81] has shown the fertility of the replicator, to understanding how innovators can earn extra profits, fund their growth and acquire larger market shares. The analysis of the diffusion of innovation is intertwined with the study of the selection mechanism in the market place. Firms that have been able to introduce new technologies are also able to increase their growth and their market shares.

5.3 RATIONALITY AND CHANGE

Two important contributions drawn directly from the philosophy of science and the early cognitive science characterize the emergence of technological trajectories as the new heuristic metaphor and a research agenda. The distinctions introduced between tacit and codified knowledge and bounded and procedural rationality, as opposed to Olympian rationality, can be considered the founding blocks.

According to Michael Polanyi (1969)[82] "knowledge is an activity which would be better described as a process of knowing" (Polanyi, 1969:132), rather than a good and agents often know more than they are able to spell in a codified and explicit way. Tacit knowledge is embedded in the idiosyncratic procedures and habits elaborated by each agent. It can be translated into a fully codified knowledge only by means of systematic and explicit efforts. An important implication of the distinction between tacit and codified knowledge consists in fact in the increase in the 'natural' appropriability of technological knowledge.

Summarizing a long debate Dominique Foray concludes that the distinction between codified and tacit knowledge is not static, as much tacit knowledge eventually is converted into a code, by means of specific activities of codification and interpretation, that are often specific to communities of practice where agent share codes and interfaces (David, Cowan, Foray, 2000; Ancori, Bureth, Cohendet, 2000; Foray, 2004)[83].

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81 Metcalfe, J.S. (1997), *Evolutionary economics and creative destruction*, Routledge, London.

82 Polanyi, M. (1969), Knowing and being, in Grene, M. (ed.) *Knowing and being, Essays*, Routledge and Kegan Paul, London, pp. 123-207.

83 Cowan, R., David, P.A. and Foray, D. (2000), The explicit economics of knowledge codification and tacitness, *Industrial and Corporate Change* 9, 211-253.

Ancori, B., Bureth, A. and Cohendet, P., (2000), The economics of knowledge: The debate about codification and tacit knowledge, *Industrial and Corporate Change* 9, 255-287.

Foray, D. (2004), *The economics of knowledge*, MIT Press, Cambridge.

Herbert Simon (1979)[84] makes two important contributions. In the first he introduces the notion of bounded rationality in order to stress the limitations of the traditional assumptions about the Olympian rationality of 'homo oeconomicus'. Bounded rationality quickly became a building block for the new emerging economics of information: the acquisition of information and the generation of signals are costly and economics need to care about.

Subsequently, however, Simon elaborated the distinction between substantive and procedural rationality. The introduction of the notion of procedural rationality has far reaching consequences as it introduces the notion of sequential decision-making. Agents cannot achieve substantive rationality for the burden of the wide range of activities necessary to gathering and processing all the relevant information. Agents can elaborate procedures to evaluate at each point in time and space the possible outcomes of their behavior, but within the boundaries of a limited knowledge and using satisfying criteria as opposed to maximization rules.

The notion of procedural rationality introduced by Herbert Simon marks a major contribution to the economics of innovation. Olympian rationality is at odds with a context characterized by radical uncertainty where nobody actually knows the outcome of a research project and even less so the next directions of technological changes being introduced. As a matter of fact the very notions of future prices and future markets cannot even be considered when technological change is taken into account. In such a context only sequential decision making based upon limited information and limited knowledge is possible.

The application of the notion of procedural rationality to economics of innovation leads to a new understanding of the basic inducement of innovation. This approach highlights the notion of creative reaction as the qualifying aspect of the behavior of innovative agents: agents innovate when their expectations are deceived and their performances fall below subjective levels of aspiration. Creative reaction is a part of the satisfying behavior of economic agents afflicted by bounded rationality but able to learn, to generate new knowledge and to modify their conditions (Antonelli, 1989)[85].

5.4 EVOLUTIONARY APPROACHES: ROUTINES AND TRAJECTORIES

The real problem economics of innovation faces is to provide an economic context to understand the behavior of economic agents facing radical uncertainty and multiple possible outcomes of their choices. A broader notion of rationality is needed as well as a more articulated understanding of the complexity of social interactions, beyond the standard price-quantities adjustments selected in a context of perfect foresight.

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84 Simon, H.A. (1979), Rational decision making in business organizations, *American Economic Review* 69, 493-512.

85 Antonelli, C. (1989), A failure inducement model of research and development expenditure: Italian evidence from the early 1980's, *Journal of Economic Behavior and Organization* 12,159-180.

Nelson and Winter (1977) [86] apply fruitfully the notions of tacit and codified knowledge and the implications of bounded and limited rationality to the theory of the firm with the notion of routines. Routines provide a clue to understanding growth as the result of the innovative behavior of myopic agents able to accumulate knowledge and to convert it into competence (Loasby)[87].

Dosi (1982)[88] implements the notion of trajectories and applies it both to understand the dynamics of innovation with respect to the sequence of well defined technologies and to the sequence of innovations introduced by well identified firms and eventually economic systems, such as regions, industries and even countries. The analysis of trajectories appears especially promising at the firm level and in the analysis of the competitive process. First-comers reap substantial competitive advantages and build barriers to entry based on their technological knowledge. Long lasting extraprofits provide financial resources to fund the incremental implementation of internal learning by doing and accumulated competence.

The notion of technological trajectory builds upon the achievements gathered with the product life cycle and makes it possible a spring of cumulative research in the discipline including the notion of technological convergence introduced by Rosenberg (1963)[89] to stress the dynamic blending of technologies and their generative relations.

Empirical research makes it possible to identify a variety of trajectories. When a variety of trajectories in a variety of technologies and firms is identified such basic questions arise: why some trajectories are 'steeper' than others; why some trajectories 'last' longer than others; why some firms fail to innovate; why some industries are less able than others to build their own trajectory. Silverberg, Dosi and Orsenigo (1988)[90] try and elaborate the analysis of the possible outcome stemming from multiple interactions among a variety of trajectories applied both to firms and technologies.

Agreement on the trajectory metaphor disappears quite rapidly when its strong deterministic bent is fully revealed. This trajectory metaphor seems to revive the old temptation to use ad-hoc technological determinism to explain the social and

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[86] Nelson, R.R. and Winter, S.G. (1977), In search of a useful theory of innovation, *Research Policy* 6, 36-76

[87] Loasby, B.J. (1998), The organization of capabilities, *Journal of Economic Behaviour and Organization* 35, 139-160.

[88] Dosi, G. (1982), Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technological change, *Research Policy* 11, 147-162.

[89] Rosenberg, N. (1963), Technological change in the machine tool industry, 1840-1910, *Journal of Economic History* 23

[90] Silverberg, G., Dosi, G. and Orsenigo, L. (1988), Innovation diversity and diffusion a self organizing model, *Economic Journal* 98, 1032-1054.

economic changes as a process of sequential alignment dictated by technology. Paradigmatic crisis arise as factors of discontinuity. New trajectories are generated and old ones decline. The origin of such changes and the emergence of new technological paradigms however remains unclear but for the implicit reference to the notion of technological opportunities and their eventual exhaustion. The ultimate origin of technological change remains exogenous and a strong deterministic character is now added.

More generally, it becomes evident that while evolutionary thinking provides a reliable and fertile approach to explain the selection process, it is unable to provide an explanation for the emergence of novelty. Evolutionary thinking is unable to disentangle from the Darwinistic framework where genotypic variations and occasional mutations are the blind product of random processes determined by genetic recombination and drift. Consistently, in evolutionary economics, innovation is not considered as the result of strategic decision-making by creative agents, but rather the stochastic result of accidental events.

In this context, characterized by the decline of the heuristic power of the notion of trajectory and evolutionary frames, increasing attention is paid to the role of historic time. The evidence, provided by economic historians and historians of technology, makes clear the key role of technological cumulability and irreversibility, localized learning and local externalities (Freeman, 1994)[91].

5.5 TOWARDS AN ECONOMICS OF COMPLEXITY

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 favors the systemic approach in that the outcome of the behavior of each agent and of the system into which each one is embedded can only be understood as the result of the interaction between micro and the macro dynamics. Complexity builds upon a number of basic assumptions: I) Heterogeneous agents. Agents are characterized by distinctive and specific characteristics as well as being intrinsically heterogeneous. II) Location matters. Location in a multidimensional space, in terms of distance among agents and their density, matters and influences both behavior and performance. III) Local knowledge. Each agent has access only to local information and local knowledge, i.e. no agent knows what every other agent knows. IV) Local context of interaction. Agents are localized within networks of relations, including transactions and feedbacks, which are specific subsets of the broader array of interactions that define their behavior. V) Creativity. Agents are creative, i.e. agents can follow some rules but they can also change the rules. They do this in response to given feedbacks, according to both their own specific characteristics and the features of local endowments, including the network of transactions and interactions into which they are embedded. VI) Systemic interdependence. The outcome of the behavior of each agent is strictly dependent on the web of interactions, which take place within the system. Hence at each point in time, the topology of the system, i.e. how the characteristics and the structural

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91 Freeman, C. (1994), The economics of technical change, *Cambridge Journal of Economics* 18, 463-514.

interactions of the agents in their relevant multidimensional spaces are distributed, plays a key role.

Complex systems are characterized by non-ergodicity, phase transition and emergent properties. When non-ergodicity applies a little shock at one point in time affects the long run dynamics of a system. Phase transitions consist in qualitative changes that can be determined by small changes in the parameters of the system. Emergent properties are properties of a system that apply at a specific level of aggregation of a system(Rosser, 1999)[92].

The merging of the theory of complexity and economics contributes the building of an economic theory of complexity based upon non-ergodicity, phase transition and emerging properties. The integration of the rich and elaborated competence of economics in dealing with systemic analysis, although in a static context, can draw on complex system dynamics, especially when the role of historic time, and the intentional behavior of rent seeking agents are taken into account, and when an understanding of the economics of innovation is integrated (Foster, 1998)[93].

The notion of path dependence as the specific form of complex dynamics applied to understanding economic systems as evolving systems makes it possible to integrate into a single and coherent framework a number of relevant and complementary contributions.

Path dependence provides a unique and fertile analytical framework which is able to explain and assess the ever-changing outcomes of the combination and interplay between factors of continuity and discontinuity, growth and development, hysteresis and creativity, routines and "free will", which all characterize economic action in a dynamic perspective which 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)[94].

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92 Rosser, J.B. (1999), On the complexities of complex economic dynamics, *Journal of Economic Perspectives* 13, 169-192.
Durlauf, S.N. (2005), Complexity and empirical economics, *Economic Journal* 115, 225-243.

93 Foster, J. (2005), From simplistic to complex systems in economics, *Cambridge Journal of Economics* 29, 873-892.

94 David, P.A. (1992), *Path-dependence in economic processes: Implications for policy analysis in dynamical system contexts*, Torino, Fondazione Rosselli.
David P.A. (1988), *Path-dependence: Putting the past into the future of economics*, Mimeo, Department of Economics, Stanford University.

As a matter of fact, 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 and yet endowed with creativity and able to generate new knowledge by means of both learning and intentional innovative strategies and by means of structural changes[95].

The notion of ergodicity deserves careful examination. When a process is non-ergodic, initial conditions (and events that occur at early points in the path) typically exert strong effects on its development and 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 analyzed and their results are fully determined and contained in their initial condition. In the theoretical economics of innovation, this extreme (some would say degenerate) form of path dependence has often been assumed: the epidemic models of 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. 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 upon the concepts of transient or 'permanent micro-level' irreversibilities, creativity and positive feedback. The latter self-reinforcing processes may work through the price system, or they may operate through non-pecuniary externalities. 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 and after which the dynamics unfold deterministically. It is the conceptualization of historical dynamics in which one 'accident' follows another relentlessly and unpredictably. Path dependence gives economists the scope to include historical forces without succumbing to naive historical determinism (Rosenberg, 1994)[96].

An important distinction emerges here between path dependent innovation and path dependent diffusion. The former takes place when the path along which the firm acts is determined by the irreversibility of her production factors and by the accumulation of competence and tacit knowledge based upon learning by doing and learning by using. In this case the switching costs firms face influence the choice of the new technology when, because of changes in relative factor costs or in the levels of output,

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95 Durlauf S. N. (2005), Complexity and empirical economics, *Economic Journal*, 115, 225–243.

96 Rosenberg, N. (1994*), Exploring the black box*, Cambridge University Press, Cambridge (Chapter 1: Path dependent aspects of technical change, pp. 9-23.)

they try and change the levels of their inputs. The latter applies to the choice of the new technology as it shaped by the markets conditions. Interdependence among users leads to increasing returns in adoption so that technologies that have been adopted by a large share of perspective users have higher chances to win out the selection process and spread to the rest of the system. The notion of path dependence elaborated by Paul David (1975, 1988, 1992) belongs to the first case: firms are induced to follow a path of technological change by their internal characteristics. The notion of path dependence elaborated by Brian Arthur (1989) [97] and Paul David (1985)[98] applies to the choice of adoption of one new technology among many possible ones and clearly belongs to the second case: new technologies are sorted out by increasing returns to adoption at the system level. The distinction between internal and external path dependence is also crucial. In the first case the emphasis is called upon the role of factors internal to each firm in shaping their path of innovation and change. In the latter, instead, much more attention is based upon the role of external factors, including feedbacks (Arthur, 1999)[99].

The introduction of innovations takes place because of disequilibrium conditions of the system and reproduces new disequilibrium conditions. Technological change is now the endogenous outcome of a disequilibrium condition, which has little chances to converge towards a new equilibrium. Actually equilibrium and technological change emerge as opposite extremes: equilibrium is possible when no technological change takes place and vice versa. (North, 1997)[100].

Hence technological change can be viewed as a form of systemic, dynamic, stochastic and finite increasing returns, which lead to, punctuated growth (Mokyr, 1990)[101]. Technological change in fact takes place when a number of highly qualified necessary conditions apply. The successful introduction of technological change is the fragile result of a complex set of necessary and complementary conditions where firms adapt continually to the changing conditions of their environment (Metcalfe, Foster and Ramlogan 2005) [102].

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97 Arthur, B. (1989), Competing technologies increasing returns and lock-in by small historical events, *Economic Journal* 99, 116-131.

98 David, P. A. (1985), Clio and the economics of QWERTY, *American Economic Review* 75, 332-37.

99 Arthur, B. (1999), Complexity and the economy, *Science* 284, 107-109.

100 North, D. C. (1997), Some fundamental puzzles in economic history, in Arthur, W.B., Durlauf, S.N. and Lane, D. (eds.) (1997), *The economy as an evolving complex system II*, Westview Press, Santa Fe, pp-223-238.

101 Mokyr, J. (1990) Punctuated equilibria and technological progress, *American Economic Review* P&P 80, 350-354.

102 Metcalfe, J.S., Foster, J. and Ramlogan, R. (2005), Adaptive economic growth, *Cambridge Journal of Economics* 30, 7-32.

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 a significant progress with respect to both the technological trajectory and the life cycle (Dopfer, 2005)[103].

Path dependence applies both to the each agent and at the system level: hence we can identify and articulate an individual and a system path dependence.

Individual path dependence provides the tools to understand the combination of hysteretic, past dependent factors, such as 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 upon 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 (Rizzello, 2004)[104] .

Firms innovate when facing changes in the expected states of the world as generated by changes in both product and factors markets (Calderini and Garrone, 2001)[105]. Innovation is induced by the mismatch between unexpected events, myopic agents cannot fully anticipate and the irreversible decisions which need to be taken at any point in time. Firms induced to innovate by irreversibility and disequilibrium in both products and factors markets search locally for new technologies. The direction of technological change is influenced by the search for new technologies that are complementary with the existing ones. This is all the more plausible when the introduction of technological changes is made possible by the accumulation of competence and localized knowledge within the firm. 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 pushes firms to limit the 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

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103 Dopfer, K. (ed.) (2005), *The evolutionary foundations of economics*, Cambridge University Press, Cambridge.

104 Rizzello, S. (2004), Knowledge as a path-dependent process, *Journal of Bioeconomics* 6, 255-274.

105 Calderini, M., Garrone, P. (2001), Liberalisation, industry turmoil and the balance of R&D, *Information Economics and Policy* 13, 199-230.

technologies. This dynamics leads firms to remain in a region of techniques, which are close to the original one and continue to improve the technology in use (Antonelli, 1997)[106].

System path dependence explores the mix of past dependent elements embedded in the structural characteristics of the system such as endowments, industrial and economic structure, market forms and organization of the networks of communication and interaction in place, with the changes to the architecture of the structure that collective action can introduce at each point in time.

The appreciation and identification of the structural conditions, which shape economic systems and are conducive to the introduction and diffusion of new technologies is one of the main results of this line of analysis. A number of complementary conditions play a role. Firms are better able to change their technologies when, because 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, the public research centers and the business community is in place (Leydesdorff and Meyer, 2006)[107]; when industrial dynamics in product and input markets can induce localized technological changes which 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 feed-back 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 over indefinitely for the exhaustion of the possible combinations (Antonelli, 2007)[108].

Path dependent complexity makes it possible to pay attention to the structural characteristics of the system in terms of the distribution of agents in the market, product, technological, knowledge space and to appreciate the architecture of the relations of communication, interaction and competition which take place among agents in assessing the rate and direction of technological change (Krugman, 1996)[109]. Some architectures are clearly more conducive than others. Architecture themselves are however the path dependent product of intentional choices of location and mobility of agents, aware of the effects of their location in such a

106 Antonelli, C. (1997), The economics of path-dependence in industrial organization, *International Journal of Industrial Organization* 15, 643-675.

107 Leydesdorff L., Meyer, M. (2006), Triple Helix indicators of knowledge-based innovation systems Introduction to the special issue, *Research Policy* 35, 1441–1449.

108 Antonelli, C. (2007), The system dynamics of collective knowledge: From gradualism and saltationism to punctuated change, *Journal of Economic Behavior and Organizaton* 62, 215-234.

109 Krugman, P. (1994), Complex landscapes in economic geography, *American Economic Review* 84, 412-417.

multidimensional space on their chances to generate and introduce timely new appropriate technological innovations (Witt, 1997)[110].

In this context the notion of generative relationship introduced by Lane and Maxfield (1997)[111] is very important. Generative relationships are "constructive positive feedbacks –that- have an obvious counterpart: as the structure of agent / artifact space undergoes ripple of changes, new agents and artifacts come into being and old ones acquire new functionalities, so identities change –and hence, old interpretations of identity bear an increasingly strained relationship with observable actions, the facts of the world. Different agents respond differently: some respond to the resulting ambiguity by generating new attributions to make sense of experienced novelty, and so attributional heterogeneity increases- increasing further the possibility that participants in other relationships will achieve sufficient attributional diversity to become generative actually, trust may result from the interactions themselves." (Lane and Maxfield, 1997:185). Generative relationships 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 distributions 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.

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 spiraling process and at a faster pace within economic systems characterized by fast rates of growth where interaction, feed-backs 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.

The circular relationship between structure and innovation: the conduct and the performances of firms are indeed influenced by the structure of the system as it stands at time t, but in turn they exert strong influences upon the characteristics of the structure at time t+1, with the introduction of innovations. A new structure is determined and firms, in order to readjust to it, 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 feedbacks between the conduct and the performance of firms, the rate and direction of technological change and structural change with a growing awareness of its evolving and historic characteristics.

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110 'Witt, U. (1997), Lock-in vs. "critical masses". Industrial change under network externalities, *International Journal of Industrial Organization* 15, 753-773.

111 Lane, D.A., Maxfield, R. (1997), Foresight complexity and strategy, in Arthur, W.B., Durlauf, S.N., Lane, D.A. (eds.) *The economy as an evolving complex system II,* Westview Press, Santa Fe, pp.169-198.

In these circumstances the generation of new technological knowledge and the introduction of new technologies can be viewed as the cause and the consequence of punctuated economic growth and dynamic increasing returns (Arrow, 2000)[112].

Innovation is the result of out of equilibrium conditions and it is the cause of out of equilibrium conditions. A clear continuity ever since the biological grafts into the trajectory and finally the systemic network approach confirms that innovation can only be understood in an analytical context which accepts to integrate the analysis of firms and agents that are continually pushed away from potential equilibrium conditions and try and react to the unexpected conditions of both products and factors markets by means of the introduction of new products, new processes, new organizational modes, new markets.

6. CONCLUSION

Economics of innovation is a distinctive area of specialization within economics, with a well defined set of competences about the origins, causes, characteristics and consequences of the introduction of technological and organization changes in the economic system. At the same time however economics of innovation pretends to be one of the main pillars of the emerging economics of complexity.

Economics of innovation is the result of a long process. The starting point is indeed the discovery of the large portion of unexplained economic growth that only technological change could be credited for. The attempt to provide an economic explanation for technological change able to integrate both the analysis of the effects and the analysis of the causes of the introduction of innovations has led to the rediscovery of a number of forgotten dynamic paths provided by the history of economic thought. Four wide-ranging heuristic frameworks can be identified: the classical legacies of Adam Smith and Karl Marx, the Schumpeterian legacy, the Arrovian legacy, and the Marshallian legacy eventually implemented by evolutionary approaches leading to complexity.

As soon as the assumptions about the exogeneity of production (and utility) functions are relaxed and agents are considered both intelligent and endowed with a specific form of creativity which makes it possible to endogenously change the basic features of the utility and production functions and hence tastes, preferences, technologies and routines, the relevance of general equilibrium analysis declines. It is difficult to conceive a system of future prices which is able to take into account the introduction of all possible new technologies in a given time horizon. There is, in fact, no longer a single attractor as firms are now credited with the capability to generate their own technological knowledge and to change their technologies and not only vary either the quantity they produce or the prices they charge.

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112 Arrow, K.J. (2000), Increasing returns: Historiographic issues and path dependence, *European Journal of History of Economic Thought* 7, 171-180.

The identification of the four lines of investigation has taken place by means of the progressive matching between a specific legacy of the history of economic thought and a specific area of investigation considered in the history of economic analysis. The classical legacy provided the basic inputs to elaborate a theory of economic growth based upon the intentional introduction of technological innovations. The Schumpeterian legacy proved fertile to analyze the role of innovation within oligopolistic rivalry and made it possible to appreciate the role of entrepreneurship as a basic engine for the continual introduction of new technologies. The Arrovian legacy provided the first elements eventually enriched in a full-fledged analysis of the economic characteristics of knowledge from an economic viewpoint. Finally the grafting of recent of biological methodologies, along the lines of the Marshallian legacy, has led to the emergence of an evolutionary approach, eventually articulated in the new complexity theory, that makes it possible to understand the process of specialization and structural change, based upon the interplay between heterogeneity, complementarity and competition that characterizes the innovation process.

Each of these four approaches has a clear focus and a distinctive area of investigation. In the second part of the XX century these four approaches in fact have first evolved in parallel with a process of specialization and consolidation of their respective areas of expertise. In a second step, however, an increasing number of lateral and horizontal contributions have been made. As a consequence quite a consistent body of knowledge articulated in a portfolio of analytical tools has emerged out of the convergence of the four approaches with the progressive integration of the different fields of investigation.

This seems to be the context in which the analysis of the conditions of dynamic efficiency can be considered so that it can become one of the key aims and scopes of contemporary work in economic theory. The merging of complex dynamic theory with a theory of the agent based upon subjective optimization implemented by the necessary consideration for creative choices in a context characterized by intrinsic heterogeneity of firms can be productive both for economics, and for building a more articulated theory of complex system dynamics.

Economic systems are more and more considered as complex dynamic mechanisms, which are able to grow and have differentiated levels of dynamic efficiency. In turn, such levels of efficiency are the outcome of the behavior of heterogeneous agents and of the structure of their relations, in that they have a differential capability to change the rules and the network of interactions. Hence, they are able to generate new technological knowledge and to introduce new technologies.

The notion of path dependence provides one of the most articulated and comprehensive frameworks 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 levels of past dependence, as well as by local creativity, interdependence and limited mobility in a structured space that affects their behavior, but is not the single determinant.

Path dependence is an essential conceptual framework, which goes beyond both the analysis of static efficiency and enters the analysis of the conditions for dynamic efficiency. It applies both to each agent, in terms of quasi-irreversibility of his 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 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 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 to overcome its intrinsic limitations stemming from its origins built on natural sciences where human decision-making is not considered. As a matter of fact the notion of path dependence is one of the main forays in the challenging attempt to apply the emerging theory of complexity to economics.