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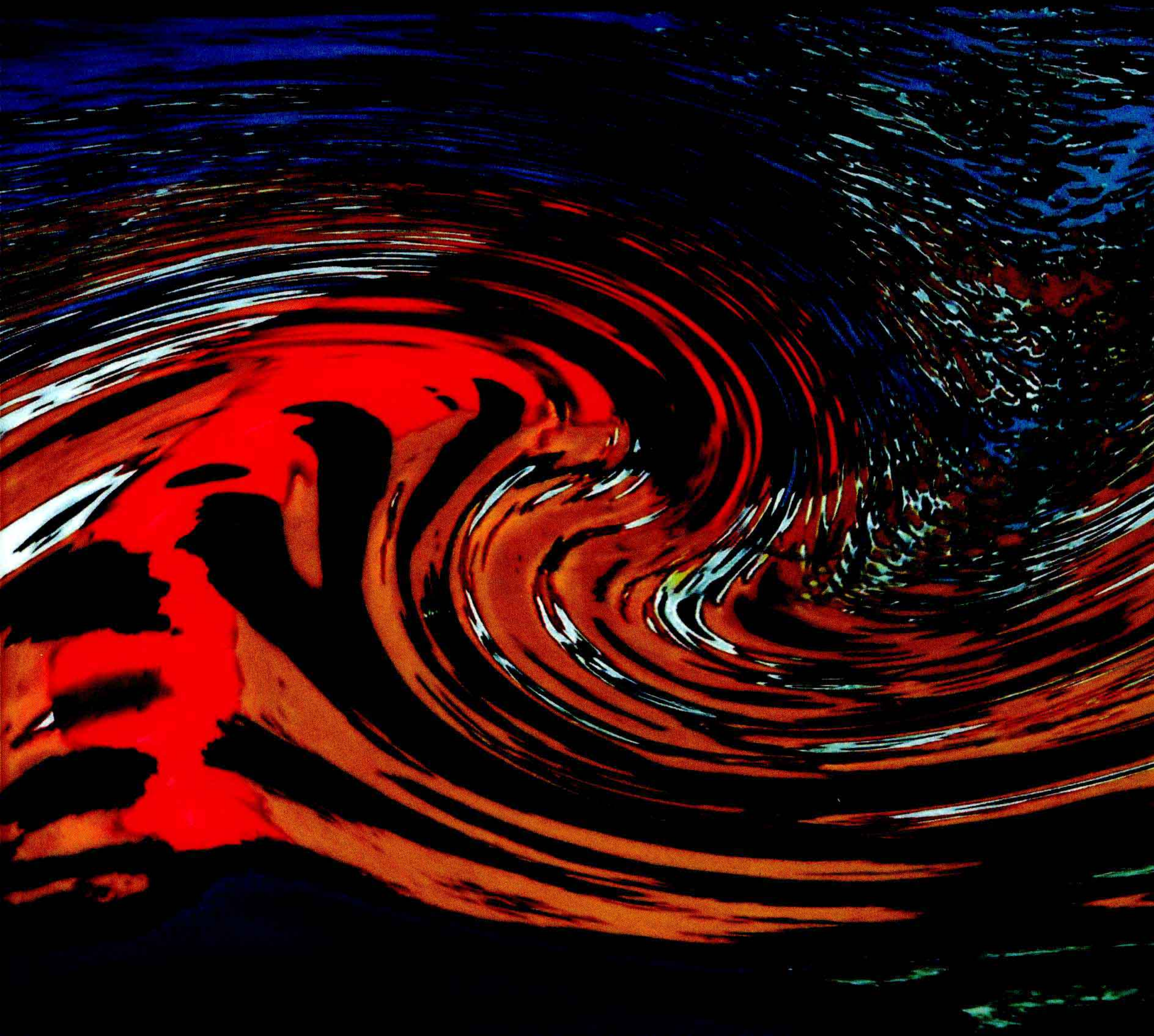
Handbook on the Economic Complexity of Technological Change

Edited by Cristiano Antonelli



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Edited by

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PART I

INTRODUCTION

1 The economic complexity of technological change: knowledge interaction and path dependence*

Cristiano Antonelli

1. INTRODUCTION

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

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

This *Handbook* presents a systematic attempt to show how, building upon the achievements of complexity theory, a substantial contribution to the economics of innovation can be implemented. At the same time it shows that an economic approach to complexity can be elaborated and fruitfully implemented. This introductory chapter articulates the view that innovation is the emergent property of a system characterized by organized complexity. It implements an approach that enables the provision of basic and simple economic foundations at the same time to analysing the outcome of the intentional economic action of agents endowed with some levels of creativity, at both micro and macro level, and to the notion of organized complexity.

According to the theory of complexity, emergence is a phenomenon whereby aggregate behaviors that arise from the organized interactions of localized individual behaviors, provide both the system and the agents with new capabilities and functionalities. Innovation and organized complexity can be seen as emerging properties of a system stemming from the combined result of the action of individual and heterogeneous agents with the structural characteristics of an organized system that is able to qualify and amplify the results of their action. The analysis of innovation as an emergent property of a system enables us to combine the individualistic analysis of innovation as the result of intentional decision making of agents with the holistic understanding of the properties of the system into which such innovative action takes place and which actually makes it possible. By the same token, the analysis of an organized complexity as an emerging property enables us to appreciate how the structural and architectural characteristics of a system are themselves the product of the interactions within the system and provide the context into which the individual reaction of agents can yield the introduction of innovations.

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

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

Second, in the complexity theory a major distinction is made between disorganized and organized complexity. In the former 'the interactions of the local entities tend to smooth each other out' (Miller and Page, 2007: 48). In the latter 'interactions are not independent, feedback can enter the system. Feedback fundamentally alters the dynamics of a system. In a system with negative feedback, changes get quickly absorbed and the system gains stability. With positive feedback, changes get amplified leading to instability' (Miller and Page, 2007: 50). Yet the theory of complexity does not provide an analysis of the endogenous determinants of the features of the system. A basic question remains unresolved in much complexity thinking: how, when and why is a system characterized by organized or disorganized complexity? The basic distinction elaborated by Hayek between cosmos and taxis, that is, spontaneous and designed order, provides basic guidance (Hayek, 1945, 1973).

The notion of organized complexity as an emerging property of an economic system enables us to grasp the endogenous dynamics of the system. The reaction of firms that happens to be creative because of the feedbacks available, affects the structure of the system and can either implement its organization or open a degenerative process. Clearly the characteristics that qualify the levels of organization of the systems complexity are endogenous to the system itself.

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

Our attempt to implement the merging of the theory of complexity with the economics of innovation provides a complementary path to recent attempts to apply the methodologies elaborated by complexity into economics, such as complex networks (see Cowan et al., 2006, 2007), percolation (see Antonelli, 1997b; Silverberg and Verspagen, 2005), and NK-modeling (see Frenken and Nuvolari, 2004; Frenken, 2006a, 2006b), for it focuses attention upon the scope of application of the basic tools of the economics of innovation to embrace the full range of analytical perspectives brought by the analysis of innovation as an emerging property stemming from the endogenous result of both the intentional, rent-seeking conduct of individual and heterogeneous agents and the endogenous characteristics of economic systems qualified by organized complexity.

This introductory chapter articulates an approach where agents are myopic: their rationality is bounded, as opposed to Olympian, because of the wide array of unexpected events, surprises and mistakes that characterize their decision making and the conduct of their business in an ever changing environment. Our agents retain the typical characteristics of economic actors, including intentional choice and strategic conduct, augmented by the attribution of potential creativity. In our approach, however, economic agents may change both their production and their utility functions. Our agents, in fact, are endowed with an extended procedural rationality that includes the capability to learn and try to react to the changing conditions of their economic environment by means of the generation of new tastes as well as new technological knowledge and its exploitation by means of the introduction of technological innovations. In this approach agents do more than adjusting prices to quantities and vice versa: they can try and change their technologies and their preferences. Agents are intrinsically heterogeneous. Their basic characteristics differ in terms of original endowments such as learning capabilities, size, and location. Their variety is also endogenous as it keeps changing as a result of the dynamics of endogenous technological change (Albin, 1998).

The determinants and the effects of this potential creativity and the context into which it can be implemented, however, require careful investigation. The actual creativity of agents is not obvious, nor spontaneous, but induced and systemic.

To investigate the determinants of the actual creativity of agents three steps are necessary. First, the incentives to change must be identified and qualified. Agents are reluctant to change their production and utility functions and a specific motivation is necessary to induce them to try and change their routines. Second, the localized context of action and the web of knowledge interactions and externalities into which each agent is embedded are crucial to make their reaction actually creative, as opposed to adaptive, so as to shape the actual effects of their endogenous efforts to change their technologies and their preferences. Third, the sequential process of feedbacks that make the creative reaction a sustained process must be identified. The creative reaction of each agent in fact is not a punctual event that takes place isolated in time and space, but rather a historic process where the sequence of feedbacks plays a key role (Arthur, 1990).

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

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

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

A Definition

Economics of innovation studies the determinants and the effects of the generation of new technological and organizational knowledge, the introduction of innovations in product, process, organization, mix of inputs and markets, their selection and eventual diffusion. Innovation takes place when it consists in actions that are able to engender an increase in the value of the output, adjusted for its qualitative content, that exceed their costs (Griliches, 1961).

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

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

Innovation is the result of a variety of activities. Learning processes of various kinds play a major role in the accumulation of the competence that is necessary to generate new technological knowledge and eventually to introduce innovations. The access to external knowledge is a crucial factor in the generation of new technological knowledge. The adoption of new capital and intermediary goods incorporating technological innovations is an essential component of the innovation process. Research and development indicators are able to grasp only a fraction of such activities. Much R&D on the other hand is funded and performed to generate novelties that are not able to increase the efficiency of the production process. As is well known, only a fraction of the technological innovations being introduced is represented by patent statistics. Neither R&D nor patent statistics account for innovations in organization, input mix and markets. Innovation counts suffer the subjective character of the claims upon which they are based. Product innovations introduced by upstream producers are often considered process innovations by downstream users (Kleinknecht et al., 2002). The distinction between innovation, adoption and diffusion is more and more blurred by the increasing awareness of the amount of creative effort that is necessary to adopt and imitate an innovation. Moreover, and most importantly, the economic analysis of innovation should take into account the time distribution of adoptions, rather than their punctual introduction. Total factor productivity indicators instead can grasp the full bundle of the economic effects of the introduction and diffusion of an innovation. Hence total factor productivity indicators are likely to provide an accurate measure of the actual amount and extent of the innovations being introduced (Crépon et al., 1998).

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

Departing from Dead-ends

This new approach overcomes the limitations of two contending approaches: general equilibrium analysis and Darwinistic evolutionary population thinking.

The merging of the theory of complexity and the economics of innovation provides a new way to integrate economic and complexity thinking and contributes to the building of an economic theory of complexity that puts the endogenous and systemic emergence of innovation at the core of the analysis. The continual introduction of new technologies and their selection is seen as the emerging and systemic property of an out-of-equilibrium dynamics characterized by path dependent non-ergodicity and interactions both among agents and between micro and macro levels. The organized complexity of the system that enables the emergence of innovations is itself the product of the recurrent and path dependent interaction of rent-seeking agents (Arthur, 1994, 1999).

Organization thinking, as distinct from population thinking, plays a crucial role in grasping the causes and the consequences of the changing structure, composition and organization of the system (Lane, 1993a, 1993b; Lane et al., 2009).

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

In general equilibrium economics, the preferences and the technologies of the representative agent and hence her production and utility functions, are allowed to change only as the result of exogenous shocks. As soon as the notion of endogenous change is introduced and heterogeneous agents are credited with the capability to change their production and utility functions in response to economic stimulations, the general equilibrium analysis appears a simplistic approach. The assumption of the necessary gravitation and convergence towards a single equilibrium point cannot be retained because of the changing centers of attraction. As soon as we acknowledge that both preferences and technologies are the result of the intentional decision making of heterogeneous actors that are part of a system of interdependencies, the foundations of general equilibrium economics collapse, yet its powerful systemic approach should be retained and implemented.

Kenneth Arrow has provided key contributions to reconcile the evidence about growth with general equilibrium analysis both with the articulated notion of learning by doing, eventually implemented with learning by using, and with the path breaking analysis of the limitation of knowledge as an economic good (Arrow, 1962a, 1962b, 1969, 1974). Building upon his legacy, the new growth theory shares the view that knowledge is characterized by an array of idiosyncratic features such as non-appropriability, non-divisibility, non-excludability, non-exhaustibility that are the cause of knowledge externalities and contribute to the continual and homogeneous introduction of innovations. The new growth theory however has not been able to appreciate the endogenous, idiosyncratic and dynamic character of knowledge spillovers. Assuming that knowledge spillovers are given and evenly distributed in time and space, the new growth theory claims that technological change takes place evenly through time and space without discontinuities and leads to smooth dynamic processes (Romer, 1994).

The main limitation of new growth theory is the underlying assumption of an automatic, spontaneous and ubiquitous trickle down of the new technological knowledge inputs into every other kind of activity in the economic system. In Aghion and Howitt's model, downstream sectors make no particular efforts to identify, understand or use the new knowledge embodied in new intermediary inputs. Technology adoption and transfer take place in the absence of effort, interaction or dedicated activity. Although perhaps not like manna from heaven, new technological knowledge rains from upstream and wets whatever is below – be it sectors or regions (Aghion and Howitt, 1992; Aghion and Tirole, 1994).

These assumptions contrast sharply with the rich evidence about the punctuated and discontinuous rates and directions of technological change and are not able to explain the wide variety across countries, regions, industries and firms in terms of rates of introduction and diffusion of innovations (Mokyr, 1990a, 1990b, 2002).

The second attempt to elaborate an evolutionary economics based upon Darwinistic population thinking, implemented by Nelson and Winter (1982) since the late 1970s, has contributed much to place innovation at the center stage of economic analysis. Evolutionary economics has built an outstanding corpus of knowledge about the characteristics of innovation and of technological knowledge with the identification of important taxonomies and significant sequences. The grafting of biological metaphors has focused on population thinking, as distinct from organization thinking, stressing the role of the natality, mortality, entry, exit and mobility of agents, while little attention has been paid to the causes and effects of the organization of economic systems. Agents are not credited with the intentional capability to change their technologies and their preferences.

Consistently with the general evolutionary frame of analysis, innovation is regarded as the product of random variations and accidental mutations, rather than the result of the intentional action of agents. The radical criticism raised by Edith Penrose against the first wave of attempts to integrate Social Darwinism into mainstream economics, based upon the well-known article by Armen Alchian (Alchian, 1950), applies very much to the second wave as well: 'to abandon [the] development [of firms] to the laws of nature diverts attention from the importance of human decisions and motives, and from problems of ethics and public policy, and surrounds the whole question of the growth of the firm of with an aura of "naturalness" and even inevitability' (Penrose, 1952: 809, 1953).

Evolutionary economics has focused much more on the analysis of the selective diffusion of new technologies rather than the analysis of the actual determinants of the generation of new technological knowledge and the introduction of innovations (Metcalfe, 1994).

The causal analysis of the determinants of technological change, however, has been left at the margin of the exploration. This seems quite paradoxical. Evolutionary economics is not able to explain the determinants of what is assumed to be the central mechanism of economic change (Hodgson and Knudsen, 2006).

Standing on Giants' Shoulders: Marshall and Schumpeter

In our approach, innovation is not only the result of the intentional action of each individual agent, but it is the endogenous product of dynamics of the system. The individual action and the system conditions are crucial and complementary ingredients to explain the emergence of innovations (see Table 1.1).

Innovation cannot be considered but the intentional result of the economic action of agents: it does not fall from heaven. Neither is it the result of random variations. Dedicated resources to knowledge governance are necessary to implement the competence accumulated by means of learning and to manage its exploitation. Agents succeed in their creative reactions when a number of contingent external conditions apply at the system level. Innovation is made possible by key systemic conditions:

> innovation is a path dependent, collective process that takes place in a localized context, if, when and where a sufficient number of creative reactions are made in a coherent, complementary and consistent way. As such innovation is one of the key emergent properties of an economic system viewed as a dynamic complex system. (Antonelli, 2008a: I)

An innovation economics approach to complexity thinking makes it possible to overcome the limitations of both general equilibrium economics and evolutionary analysis into a complex dynamics approach. It builds upon the integration of Schumpeterian analysis of innovation as a form of reaction, to the changing conditions of product and factor markets, with the Marshallian partial equilibrium approach to localized increasing returns based upon circumscribed externalities. This approach contrasts the general equilibrium analysis where economic agents are indeed embedded in a systemic analysis but are not supposed to be able to change purposely their technologies and their preferences. This effort can contribute a complex dynamics where technological change is the central engine of the evolving dynamics viewed and it is the result of the creative response of intentional agents, embedded in the organized complexity of a system populated by interacting and reactive agents (Antonelli, 2007, 2008a, 2009a).

Table 1.1 Dead ends and new prospects for the analysis of systems where innovation is an endogenous, TFP-enhancing emergent property

	Micro	Meso	Macro
General equilibrium	The representative agent can adapt but cannot innovate	Market transactions	Low-level static complexity
Marshallian partial equilibrium	Intrinsic heterogeneity and variety of agents and locations	Localized increasing returns based upon externalities	Uneven growth
Arrovian legacy	Learning; knowledge as an imperfect economic good	Knowledge spillover	Spontaneous, even and steady dynamic equilibrium
Darwinian evolutionism	Random variations and occasional mutations	Selection based upon replicator dynamics; emergence of dominant designs	Growth and change based upon selective diffusion of innovations
Complexity cum innovation	Innovation as an emergent property when individual reactions based on generative relations match organized complexity	Knowledge governance; non-ergodic changes in the organization of structures and networks	Growth and path dependent change based upon innovation within organized complexity

The Marshallian approach provides the basic frame for a systemic understanding of the behavior of heterogeneous agents that are interdependent within a dynamic context characterized by localized increasing returns and increasing levels of division of labor engendered by specialization. The Marshallian partial equilibrium analysis provides a rich analytical apparatus that emphasizes the idiosyncratic variety of agents and markets that interact in a systemic context characterized by endogenous structural change. The Marshallian partial equilibrium enables the use of the foundations of microeconomics as they provide the analytical context into which the maximizing conduct of individual agents can be interpreted and yet makes room for understanding the interactive process of structural and technological change. The integration of partial equilibria, however, does not lead to general equilibrium. As Young (1928) has shown, each change in a component of the system modifies its structural composition and organization and feeds in turn new ripples of technological change via new flows of externalities. Technological change and structural change are intertwined and necessary components of an aggregate and systemic dynamics (Foster, 2005; Metcalfe et al., 2006).

For these reasons the Marshallian approach can be retained and integrated with the Schumpeterian and classical approaches that stress the role of the creative reaction of firms caught in out-of-equilibrium conditions into an economics of complexity that emphasizes the endogenous emergence of technological change and the continual transformation of the structure of the system (Schumpeter, 1941; Downie, 1958).

The aggregate dynamics of the system, in fact, is far from the assumptions of an even, smooth and homogenous pace. It is instead characterized by strong elements of contingent discontinuity as well as historic hysteresis (Anderson et al., 1988). The understanding of the dynamics of the system requires the grasping of the causes and determinants of both individual action and the changing centers of gravitation of the system (Blume and Durlauf, 2005).

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

The reappraisal of a somewhat forgotten contribution by Joseph Schumpeter (1947b) provides basic support in this endeavor. The direct quote of a key portion of this text seems most appropriate here:

> What has not been adequately appreciated among theorists is the distinction between different kinds of reaction to changes in 'condition'. Whenever an economy or a sector of an economy adapts itself to a change in its data in the way that traditional theory describes, whenever, that is, an economy reacts to an increase in population by simply adding the new brains and hands to the working force in the existing employment, or an industry reacts to a protective duty by the expansion within its existing practice, we may speak of the development as an adaptive response. And whenever the economy or an industry or some firms in an industry do something else, something that is outside of the range of existing practice, we may speak of creative response.

Creative response has at least three essential characteristics.

> First, from the standpoint of the observer who is in full possession of all relevant facts, it can always be understood *ex post*; but it can practically never be understood *ex ante*; that is to say, it cannot be predicted by applying the ordinary rules of inference from the pre-existing facts.

This is why the 'how' in what has been called the 'mechanisms' must be investigated in each case.

> Secondly, creative response shapes the whole course of subsequent events and their 'long-run' outcome. It is not true that both types of responses dominate only what the economist loves to call 'transitions', leaving the ultimate outcome to be determined by the initial data. Creative response changes social and economic situations for good, or, to put it differently, it creates situations from which there is no bridge to those situations that might have emerged in its absence. This is why creative response is an essential element in the historical process; no deterministic credo avails against this. Thirdly, creative response – the frequency of its occurrence in a group, its intensity and success or failure – has obviously something, be that much or little, to do (a) with quality of the personnel available in a society, (b) with relative quality of personnel, that is, with quality available to a particular field of activity relative to the quality available, at the same time, to others, and (c) with individual decisions, actions, and patterns of behavior. (Schumpeter, 1947b: 149–50)

Innovation and Organized Complexity as Emergent Properties of an Economic System

In our approach, innovation is an emergent property that takes place when complexity is organized, that is, when a number of complementary conditions enable the creative