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Exaptation, degeneracy and innovation

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Abstract In innovation processes, exaptations are innovation-development processes through which an initial attribution of new functionality to existing artifacts leads to new artifacts and eventually new markets. In this article I focus on the theoretical foundations of these processes, proposing a theoretical framework to analyze them. The essay provides a contribution in the following two directions:

- a discussion of the different levels of organization through which exaptations emerge in a market system;
- an analysis of the complex links between exaptation and degeneracy (a many-to-many rather than one-to-one map between structure and function).

Using this theoretical framework, I focus on the need for an analysis of the consequences of exaptations, arguing that exaptations may contribute to emerging degeneracy, which, in turn, may trigger further exaptations. In market systems one form of degeneracy is the coexistence of many structurally different artifacts providing at least in part the same functionality. I present historical examples that suggest that degeneracy increases the complexity of the system: the attribution of functionality previously provided by existing artifacts to new artifacts potentially able to provide them in a new way is a significant process giving raise to new artifacts and new markets.

Key words: *Innovation – Exaptation – Degeneracy – Adaptation*

JEL classification: *O30, O33, D20*

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1. Introduction

My aim is to contribute to a theory of exaptation phenomena in innovation processes. The term "exaptation" was coined by Gould and Vrba (1982) in the context of evolutionary biology, to indicate the origin of characters that are useful for survival – and thus "apt" – but were not selected for this purpose, and cannot therefore be said to be "ad-aptive". The contribution of exaptations to survival is due to the new way through which features formed for other reasons, or even for no reason tied to functionality, are used by the organization of which they are a part: these features are useful for survival in virtue of their *ex* form, they are *ex-apt*. Feathers, for example, originally had the function of thermoregulation. Later they were co-opted by birds for flying. In other words, feathers were exapted for a purpose different from the original one, through a process that has made them "apt" for such use (Gould, 2002 p. 1232). In innovation processes, exaptations are new artifacts and new organizations realized initially by using, in a new way, existing artifacts and organizations. Such new artifacts and organizations may require new markets.

The present essay addresses the following two key research issues, crucial for an analysis of exaptation in innovation processes:

(a) the role of new attributions of functionality as a starting point for the exaptation process;

(b) the need for an analysis of the consequences of an exaptation; in this connection my attention focuses on the transformation of the relationships between users and producers, hence on the possibility of the emergence of a new market system: as a market system for a completely new family of artefacts or as new market niches for new types of artifacts of an existing family.

The essay is intended to provide a contribution to the theoretical foundations necessary for an analysis of exaptations in the following two directions:

(a) a discussion of the different levels of organization through which exaptations emerge in a market system;

(b) an analysis of the relation between exaptation and degeneracy, where degeneracy is "the ability of elements that are structurally different to perform the same function" (Edelman and Gally, 2001 p. 13763); I use two historical examples to show that exaptation contributes to emerging degeneracy and that, at the same time, exaptation is triggered by degeneracy.

Some significant examples of exaptation in the process of innovation are reviewed by Dew, Sarasvathy and Venkataraman (2004, pp. 73-79): the phonograph, the laser, the architecture of agricultural tractors and the CD-ROM. In 1877 when he invented the phonograph, Edison believed that it should be used "to take dictation without the aid of a stenographer" (Basalla, 1988 p. 139). While allowing for other possible uses, Edison attributed to his invention a well-defined functionality. Consequently, for ten years he undertook attempts to market the phonograph as a dictating machine. However, this functionality was not recognized by potential users, and Edison's efforts were unsuccessful. The phonograph that Edison had conceived for a particular use was successfully co-opted for a different one: a tool for automatically playing popular music in the first jukebox, which became the first major use of the new technology. Although Edison had considered the possibility of using the phonograph as an instrument to reproduce music, he had certainly not contemplated the jukebox as a possible use of his invention and he never recognized it as legitimate use of the phonograph.

Another well-known story of exaptation is that of the laser, whose invention is attributed to Charles H. Townes in the early 1950s. The first laser was realized in 1960 by Theodore Maiman. The laser was designed with no specific purpose. At the end of the 1950s, when laser technology was implemented, it was thought that it would find no application that could be commercially exploited in telecommunication, and the lawyers at Bell Labs were against patenting it (Rosenberg, 1996). Yet a few decades later the laser was being employed, with complementary innovations and already existing technologies, in many fields, giving rise to several new products. Its applications in microsurgery and telecommunications, in new measurement systems, in the identification of bar codes and in cutting devices are all instances of exaptation of laser technology.

A third example of exaptation is the architecture of the agricultural tractor. In the late nineteenth century various inventors tried to use the internal combustion engine as an energy source for tractors, substituting animal power. Soon these inventors realized that to assemble a heavy internal combustion engine and an equally heavy chassis would have resulted in a machine too heavy to be used in agriculture. This problem seemed insurmountable until someone had the idea to use the engine itself as a chassis. To the engine block were attached not only the gearbox and the drive axle components, but also the front axle, the ancillary equipment and the driver's seat. "Thus the chassis of a tractor is actually an exaptation of the engine-gearbox-axle equipment that was necessary to make the tractor a tractor in the first place. Once the exaptation was produced, it was of course widely imitated by all producers, becoming the standard architecture for the tractor industry up to the present day" (Dew, Sarasvathy and Venkataraman, 2004, p. 79).

Another example of exaptation is the compact disk. Originally developed by James T. Russell as a system to reproduce sound using light as a medium, it was patented in 1970 as a digital-to-optical recording and playback system. Thus, the compact disc was developed to improve the quality of the reproduction of sound compared to vinyl records. However it was later exapted for another use: a data storage tool for computers. To this end, several improvements were made that allowed using the CD-ROM as a storage tool for all forms of data.

These examples are just the tip of an iceberg. According to Mokyr (2000, pp. 57-58), exaptation phenomena are a ubiquitous characteristic in the history of technology. The analysis of the process of exaptation is a key element to a better understanding of the dynamics of the innovation processes. Lane (2010) argues that exaptation introduces a positive feedback in innovation processes and Bonifati (2010) that it is a foundational concept of a complexity theory of innovation[1]. As discussed more extensively in section 2, the presence of exaptation's phenomena does not allow to derive the origin of technologies and products from their current functionality. Hence, an analysis of the process by which a new functionality attributed to an existing artefact leads to a new artefact is required. For this reason, the analysis of exaptations represents a possible alternative to the "adaptation through selection" paradigm in examining the innovation dynamics.

What are the theoretical foundations of exaptation in innovation processes? Dew, Sarasvathy and Venkataraman (2004, p. 75) seek the answer in two characteristics of artifacts, and of technologies in particular. The first characteristic is that a technology as complex system is characterized by the property of "near decomposability" (Simon, 1962). According to this property an artifact can be divided into subparts, each of which is approximately independent of the behavior of the other subparts. Hence, each subpart can be exapted. The second feature of technologies is that they result in a virtually endless and unpredictable list of possibilities and consequences. In the present essay I relate these two characteristics of technologies to a more general context. As the examples just cited show, a technology has a number of potentialities which can be imagined, but whose realization depends on two general processes: (a) the process of attribution of new functionalities and (b) the process through which an exaptation may generate new artifacts and new markets. For example, in addition to that of dictating machine, in a article in 1878 Edison specified nine other possible uses of phonograph: "provide 'talking books' for the blind; teach public speaking; reproduce music; preserve important family sayings, reminiscences and the last words of the dying; create new sounds for music boxes and musical toys; produce clocks capable of announcing the time and a message; preserve the exact pronunciation of foreign languages; teach spelling and other [w]rote material; and

record telephone calls" (Basalla, 1988 pp. 139-140). Of all these possibilities, what was done was crucially influenced on the attribution of a new functionality to the phonograph.

The essay is organized as follows. Section 2 is devoted to a discussion of the difference, and the possible relationship, between exaptation and adaptation. In Section 3, in order to provide an appropriate ontology for the analysis of exaptation phenomena, I define artifacts and market systems in terms of patterns of interactions between producers, sellers, consumers and organizations in terms of different forms of co-ordination of interactions. In section 4, I relate exaptation phenomena to different levels of organization in a market system and provide a framework for the analysis of the exaptation process. In section 5 I use the theoretical framework put forward in the preceding section and historical examples to offer a specific and original contribution on innovation theory. I argue that in the dynamics of innovation processes exaptation contributes to emerging degeneracy and that, at the same time, exaptation is triggered by degeneracy. Section 6 concludes the essay.

2. Exaptation versus adaptation

For the purposes of the present essay it is necessary to introduce first of all a rigorous definition of exaptation phenomena in connection with the social processes of innovation in which the creation of new products and new markets changes qualitatively the relationships between producers, sellers and consumers. In my definition exaptation processes give rise to new artifacts and new markets whenever new functionalities activate new uses of a technology giving rise to transformations in the relations between production, technology and consumption (Bonifati, 2010 p. 754). The attribution of new functionalities to existing artifacts leads to new artifacts through a development process that transforms existing products and technologies into new products that satisfy the new functionalities. In all cases of exaptation cited above, and in those to be examined further, after the initial attribution of new functionalities there is a process through which new artifacts emerge that are "apt" to satisfy these functionalities. Often this development process is described as an "adaptation". Therefore, a relevant issue concerns the difference, and the possible relationship, between exaptation and adaptation in relation to innovation processes.

In the traditional theory of production, an innovation is a new combination of factors of production. Innovations are then adopted in a more or less passive way, neglecting, generally, the process leading to many product improvements as a result of interactions between producers and users (Rosenberg 1976; 1982).

Since the 1950's with the contribution by Alchian[2] and more intensely after the publication in 1982 of "An Evolutionary Theory of Economic Change" by Nelson and Winter, adaptation through a process of selection and variation has become a paradigm of innovation theory. Following organization theory as developed in March and Simon (1958) and Cyert and March (1963), in Nelson and Winter's theory the firm's activity is described in terms of routines through which each firm, producing a well-defined product, pursues, in conditions of bounded rationality, a satisficing objective defined in terms of a positive profit. So satisficing behaviour is substituted for traditional profit maximization. Nelson and Winter distinguish between three classes of routines: (a) short run routines, given the capital stock and other fixed factors; (b) routines governing investment decisions; (c) procedures that generate new routines. The core of the theory is the mechanism that generates selection and variation. At any time, with existing routines and existing capital stock, along with other state variables, individual firms choose the levels of input and output. The profitability of each firm depends on these decisions and on market conditions of supply and demand. Profitability, in turn, is the heart of investment decisions through the application of second-class routines. Hence the more profitable a firm, the more it grows. Different levels of growth in firm size involve, in turn, different levels of market input and output, different relative prices and, consequently, different profitability signals for individual firms, and so on. According to Nelson and Winter, this selection mechanism determines the rate of expansion and contraction of individual firms in a way similar to natural selection, where routines are similar to the genetic code of biological organisms. In their model, given the selection criterion (ex post profit), the selection mechanism generates differential firm growth rates resulting in a particular industry structure.

Innovation arises from a change of routine *within* individual firms. Firms follow the third class of routines to change existing routines through a search activity whose success depends (stochastically) upon a number of variables, the most important of which is R&D spending, which, in turn, depends on the firm's size. New routines, if sufficiently permanent, are then submitted to the selection mechanism. In this type of theory, innovation (variation) is the firm's response to changes in external conditions, as signalled by an ex post lowering of profitability of its existing routine set[3].

The ultimate conclusion of Nelson and Winter's theory is that through variation and selection firms adapt to market conditions. For my purposes, what is relevant is the implication of this adaptationist perspective. As a result of such a perspective, the origin of routines and products should derive entirely from their actual (current) utility: that of being routines and products more ad-apted to actual market conditions. The fundamental difference between the meaning of adaptation

and that of exaptation is, then, the following. The first term indicates that through a selection-variation process the origin of an artefact can be derived from its current functionality. Exaptations, instead, are made by using in new way artifacts, including technologies, already available for other purposes. The origin of the artifacts created by exaptation processes can not be derived from their current utility[4].

Exaptation requires an emergence process. In the next three sections I examine the process by which new artifacts and new markets emerge from new functionalities. However, I want now to highlight that this process of emergence differs, despite superficial similarities, from the idea that the application of existing technological knowledge to a new domain depends on a process of adaptation. According to Levinthal (1998) development of existing technology into a new application domain is similar to a process of speciation. As such it requires the existence of new niches within which innovative entrepreneurs find the necessary conditions to develop a technology already applied to a domain, in a new application domain. Within this framework of analysis, "[t]he nature and pace of technological change are driven by two elements of the selection process. The first is a process of adaptation: the technology becomes adapted to the particular needs of the new niche that it is exploiting. The second element corresponds to the resource abundance of the niche. As a result, the mode of development is influenced by the particular features of the niche, while the pace of development is driven by the resources that this niche is able to provide" (Levinthal, 1998 pp. 220-221).

Dew, Sarasvathy and Venkataraman (2004, pp. 80-81) interpret this framework in terms of an initial exaptation followed by a subsequent adaptation. According to the framework of analysis put forward in the following sections, by contrast, the process of exaptation begins with the attribution of new functionality – to existing artifacts or to unexplored potential of existing technologies – within the system of relations that characterizes a market system. That the initial attributions of new functionalities give rise to new artifacts and new markets depends on the emergence of new systems of relations between agents, old and new, that populate the market system. The emergence of these new relationships leads to entirely new markets and/or new niches in existing markets. It follows that market niches are not assumed to already exist in the process of exaptation.

To sum up:

- According to the *adaptation* perspective, well defined technologies and products are adopted for their function through a process of selection and variation. In this perspective, the historical origin of existing technologies and products should be inferred from their current utility.

- According to the *exaptation* perspective, existing technologies and products have intrinsic but latent potentialities available for other uses provided that new functionalities are attributed to them.
- Exaptations must be examined in terms of their consequences. In particular, the process by which an exaptation generates new artifacts and new markets *apt* to provide the new functionalities must be examined. Hence, an exaptation process includes an initial exaptation and a subsequent process of "*aptation*" characterized by a continuous ongoing change in which the creation of new products requires, and gives rise to, the implementation of a range of internal and external business conditions.

3. Artifacts, market systems and organization(s): an ontology to define exaptation

A central idea for understanding the meaning of the concept of exaptation is that new products, new markets and new organizations emerge from the relations between producers and users of artifacts. Although this idea is amply supported by the history of innovations, it does not form part of standard economic theory, which looks at the production process in terms of a one-way relation from "factors of production" (labour and capital) to output.

I examine exaptation processes in a different perspective. Hence, to proceed with a theory of exaptation, we need an appropriate ontology founded on the principle that entities embedded within the social realm interact and generate processes of change in historical time (Dopfer and Potts 2004, especially pp. 204-208, and 2008, pp. 3-4). Such an ontology allows to define: (a) artifacts and markets in terms of patterns of interactions between producers, sellers and consumers and (b) organization in terms of different forms of coordination of interactions. In this perspective, products, markets and organizations are the result of the emergence of a series of social and economic conditions and relations: they are social entities.

Artifacts include a wide range of objects or interactions, both tangible (consumer goods, capital goods) and intangible (services or legislations). I define an artifact in terms of three sets of elements: (a) the functionalities, i.e. the properties attributed to it in relation to its usefulness for some purpose; (b) the human labour oriented by a project and directed towards creating processes of transformation; (c) its purely material characteristics. The interaction between matter, human labour and functionality is, by its very nature, a social process. Individuals must come into contact with other individuals in order to generate the

flow of information, functionalities, technical knowledge and skills by which an artifact *becomes* generally utilized and produced.

Artifacts are currently produced, sold and used within a system of interactions between producers, sellers and users. In a market system, these interactions are organized – i.e. they have found appropriate forms of coordination. In traditional neoclassical economic theory, markets are anonymous and abstract entities in which demand and supply functions determine clearing prices. Hence market relationships are reduced to market transactions between maximizing agents coordinated by the price mechanism. In this context, competition is mainly price competition.

In the strongly reductionist formulation of neoclassical economic theory, markets ultimately do not have a specific story. The origin and development of specific relationships that give rise to markets do not matter. Instead, we need a market definition that allows examining and reconstructing the market relations in different historical and social conditions. I adopt the definition of market system as "a set of agents that engage with one another in recurring patterns of interactions, organized around an evolving family of *artifacts*" (Lane and Maxfield, 2005 p. 36). In this formulation, markets are entities in which particular forms of interaction between agents and artifacts take place and in which a series of activities is generated. These range from design, production and exchange of artifacts to the creation of new attributions of functionality, of new skills, of new artifacts and new patterns of interaction.

The organization of relationships between agents and artifacts requires some process of coordination. As it is well known, in a pure neoclassical world all transactions should be through the market without the need for alternative forms of organization, such as the firm. According to Coase (1937 and 1972) and Williamson (1986), the firm is justified by the existence of transaction costs. This perspective generates the dichotomy between two different forms of organization: planned-coordination within the firm and spontaneous co-ordination through the market. In the standard theory of organization, the firm is like an island "of conscious power in this ocean [the market] of unconscious co-operation" (Robertson, 1923 p. 85). Note that both forms of organization assume that market prices are able to efficiently coordinate all economic activities. In fact, the existence of a form of organization alternative to the market is not justified on the assumption that prices could not play a coordination role, but by the mere existence of transaction costs. In the standard economic theory, deliberate co-operation between firms can take place only in "special" cases, namely as a form of restricted competition.

As noted by Richardson (1972), "the dichotomy between firm and market leaves out of account … the dense network of co-operation and affiliation by

which firms are inter-related" (p. 883). Hence, "by looking at industrial reality in terms of a sharp dichotomy between firm and market we obtain a distorted view of how the system works" (p. 884). Richardson refers to different forms of organization resulting from the need to coordinate similar activities (through the direction within the firm) or dissimilar activities (through various forms of cooperation between firms).

> "Here then we have the prime reason for the existence of the complex networks of co-operation and association … They exist because of the need to co-ordinate closely complementary but dissimilar activities. This co-ordination cannot be left entirely to direction within firms because the activities are dissimilar, and cannot be left to market forces in that it requires not the balancing of the aggregate supply of something with the aggregate demand for it but rather the matching, both qualitative and quantitative, of individual enterprise plans." (Richardson, 1972 p. 892).

Following Richardson, I believe that the price mechanism is unable to guarantee the coordination of relations between agents and artifacts. I define an organization in terms of different forms of co-ordination of different patterns of interactions between agents and artifacts in a market system (Lane et al., 2009). In this approach, it becomes crucial to focus on what the traditional co-ordination approach through price mechanism totally ignores (and hides): the different levels at which coordination of relationships between agents and artifacts are achieved.

4. A framework for the analysis of the exaptation process

In describing the dynamics of exaptation processes, the key starting point of my framework is the users-producers interaction networks in a market system. Rosenberg demonstrated that innovations arise and spread within a series of relations among the firms, and among these and the final users of goods and services. The overcoming of economically relevant constraints – whether technical, social, legislative or natural – and complementarities are key aspects of the process through which innovations are generated (Rosenberg, 1976). In analysing this process, the market system, as defined above, is the most appropriate unit of analysis. In a market system, users-producers interactions generate knowledge and new capabilities, new users and producers, new functionalities, and new artifacts. What is relevant for the present essay is that new artifatcts and new markets emerge as a result of exaptations through processes nested in existing market systems and so in existing recurrent patterns of interaction. The key research issue then becomes to examine two related processes that take place in historical time: (a) the attribution of new

functionalities as a starting point for the exaptation process and (b) the emergence of new artifacts and new markets.

4.1 The exaptation process at different levels of organization

I analyze the exaptation process in a market system at different levels of analysis[5] each of which has a different type of organization of interactions:

(a) At the microlevel, interactions between agents and artifacts give rise to attributions of functionality. At this level, the organization of interaction requires that agents come into contact with artifacts. New functionalities are attributed at individual level (individuals or groups of individuals): by producers in a stage preceding market demand (through a series of links with potential customers, such as advertising or trade fairs) and/or by consumers who, using an artifact, discover new functionalities.

(b) At the mesolevel, knowledge and capabilities emerge through interactions between users and producers in consumption and production activities. At the mesolevel, recurrent patterns of interactions emerge organized around individual plans of actions in consumption and production activities.

(c) At the macrolevel, patterns of interactions are consolidated at a higher level of coordination through conflict, negotiation, and sharing of common interests and systems of beliefs.

The distinction between different levels of analysis of interactions in a market system allows us to examine the exaptation process based on three interrelated analytical steps: (a) the attribution of a new functionality (microlevel); (b) the use of existing patterns of interaction end/or the development of new one to make it possible to achieve new technologies and artifacts apt to the new functionalities (mesolevel); (c) the need for a higher level of re-coordination of existing and new patterns of interactions (macrolevel).

In the process of exaptation an attribution of a new functionality has the meaning of a new use of an existing technology or product that emerged for another purpose. At this first step of the exaptation process there is a sort of imbalance in the market system. There is a new functionality not matched by an effective production capacity (there are not yet fully adequate knowledge and skills). A necessary condition for the market system to activate the development of new knowledge and skills is that the new functionality is communicated between potential users and producers. New information flows from users to producers. In “the dense network of co-operation and affiliation by which firms are inter-related”, this condition is satisfied by the fact that users communicate to potential producers the new specifications required for the new use of an existing

technology or product (and *vice versa,* when the producers propose new functionalities). Note that no price signal could play this role: there is no price for the new technology or new product yet to be developed.

In the second step of the process, new functionalities and new information activate, through user-producer interactions, new knowledge, new capabilities, new users and producers. From this process, new patterns of interactions and new competence networks emerge. Complementary technologies required for new technologies or new product may be developed and the attributions of the new functionalities may be better articulated. In developing new technologies and new products the process of exaptation has the result that new technologies become suitable for new functionalities, some of which can co-evolve with the development of the new technologies and the new products.

In order to consolidate and maintain existing and new competence networks, the completion of the process of exaptation requires an explicit re-coordination at the macrolevel. In this third step, the re-coordination through conflict, negotiation, and sharing of common interests and systems of beliefs involves three basic dimensions: the organization within firms, the relationships between the firms and the relationships between producers and consumers. This re-coordination can be achieved either by using existing organizational models or, where necessary, creating new forms of coordination.

To sum up, through exaptation processes existing technologies are co-opted in (or linked with) new kinds of uses as the result of new functionalities attributed to possible uses of the technology which were still unknown at the time of its introduction. New functionalities generate new artifacts and new markets in connection with the changes in the relations between technology, production and consumption.

The exaptation perspective shows the limits of the idea that a technology "adapts" to certain uses, as if those uses were already existed waiting for a new technology to adapt. It is also evident that exaptations have nothing to do either with the notion of externality or with the idea that innovations are essentially new combinations of existing ideas (Dew, Sarasvathy, and Venkataraman, 2004 pp. 73-74). Externalities by definition are the consequences of the actions of individual agents on a third party (e.g. consumers or businesses) who are not directly involved in those actions. Exaptation, instead, is the result of the transformation of relations *between* agents in a market system triggered by new functionalities attributed to existing artifacts. For the same reason, exaptations are not due to new combinations of ideas carried out in a creative way by the entrepreneur-innovator (Schumpeter, 1911). A process of exaptation does not combine existing technologies in new ways. By exaptations, existing technologies are co-opted into new uses. Finally, exaptations should not be confused either

with accidental discovery (serendipity) or with the unintended consequences of technology. Indeed, exaptations are intentional actions of attributions of new functionalities and subsequent developments of new artifacts.

4.2 Exaptation and price emergence

The proposed theoretical framework suggests that in exaptation processes, price emerges between the meso- and the macro level. Setting the price, in fact, requires: (a) the emergence of standard unit cost (through meso level emergence of knowledge, information, capabilities, users and producers); and (b) a threshold level of coordination, required in order that a satisfactory level of profitability can emerge (given a minimum level of the rate of return on capital invested). Prices, setting reliable conditions of profitability, contribute to maintain producers' activity (meso level) and coordination (macro level). Hence, price emergence, producers' activity and coordination are connected through positive feedbacks. During the exaptation process these conditions are in progress and setting a price may require several revisions. Hence, for the decision whether to continue production or not the price is a reference less reliable compared to the quantities actually sold (say at a conventional minimum price).

4.3 Exaptation and uncertainty

Last, but not least, exaptation phenomena occur under conditions of uncertainty. New artifacts, new patterns of interaction around their production and use, and new attributions of functionality generate perpetual novelty in innovation contexts, which makes prediction impossible. The uncertainty involving the processes of creation of new products and new markets goes well beyond uncertainty regarding expected demand. In innovation processes, there is uncertainty not only because agents are unable to exhaustively classify the consequences of actions they contemplate taking, but also because some of the very subjects, objects and criteria of value with which these consequences of their possible actions would have to be classified simply *do not exist* at the historical moment in which agents must act. This kind of uncertainty has been called *ontological uncertainty*, whose implications for the analysis of innovation are fully discussed by Lane and Maxfield (2005)[6].

5. Exaptation and degeneracy

To understand the deeper meaning of exaptation, it is useful to consider the

following two types of potential uses that allow exaptation processes and that form what Gould calls the "exaptive pool" (Gould, 2002 pp. 1270-1295):

(1) Different uses of things already in use but *potentially usable* in different ways. This type of exaptation arises from the intrinsic potentials of (or "inherent potentials" to) something, not from existing things.

(2) Uses of available things or characters *not yet used*. This type of exaptation is derived from things available but unused. Things not in use can result: (a) as structural elements of an architecture that have no function in that architecture, (b) as elements that have lost their original functionality without having gained a new one.

In innovation processes, exaptation examples of the first type include the phonograph and the laser, while the architecture of the tractor is an example of exaptation of the second type[7]. In this section I discuss an aspect of the exaptation process, not present in the current literature on this subject, focusing on the notion of degeneracy. This is a characteristic of biological systems discussed by Edelman and Gally (2001), who define it as "the ability of elements that are structurally different to perform the same function or yield the same output" (p. 13763). A well known example of degeneracy in neurobiology is the convergent-divergent connectivity of the human brain. For example, different brain structures can influence motor function, in series or in parallel. As a consequence, after a localized brain lesion, frequently alternative pathways ensuring the same functionality emerge.

In what follows, I use the framework put forward in the preceding sections and two historical examples to show that in exaptation-innovation processes degeneracy may emerge and that, at same time, degeneracy may trigger further exaptation processes. The analysis of these processes will be conducted at micro and meso level, leaving to further research the analysis of the macro level. The examples relate to the new artifacts emerged from the use of the print potentials in the second half of the fifteenth century in Florence[8]. The book as artifact may be defined by the combination of the following four elements: (a) functionality; (b) content (subject, language); (c) technical and physical properties (reproduction techniques and material used as support for the reproduction of texts); (d) exterior characteristics (size, fonts, presence/absence of illustrations, etc.).

For the present purposes it is important to introduce a distinction between generic (or potential) and specific functionalities. For every book there is a *generic* or *potential functionality* inherent to the written text: preserving in written form a multiplicity of human activities, ranging from speculative thought to description of economic activities, transmission of emotions, representation of images. The *specific functionalities* that readership attributes to each type of book

depend on the content and exterior characteristics of the books and, more important, on the purposes for which each type of book is used. In the mid-fourteenth century in Italy and Europe different types of manuscripts were produced, such as liturgical books in large format, prayer books of smaller size, academic texts, especially of legal argument, and humanistic books, in particular the texts of Latin and Greek classical authors. University manuscripts were produced, on a large scale, in Paris and Bologna, sites of the most important and oldest universities in Europe. Florence was the most important production center of humanistic manuscripts sold throughout Europe. Manuscripts were reproduced on order, through a complex system of relations – governed by appropriate contracts – between booksellers, stationaries, scribes and clients.

Making it possible to reproduce texts in many copies, fast and cheap, the printing technology has opened up new potentialities. At the same time it required a qualitatively new relation between production, technology and consumption (Bonifati, 2008 and 2010). Unlike manuscripts, in general printed books are not produced on order but for a *potential* demand. It follows that printed books production requires to be funded in advance of the actual sales. The search for links with potential customers became a necessary condition for production and an active force in the construction of a market system[9]. In Florence the first books were printed in 1471, in a press located in the Dominican convent of San Jacopo di Ripoli. They were mainly religious and devotional texts, texts of vernacular poetry and grammars: books very different from the precious humanistic manuscripts that Vespasiano da Bisticci, the most prominent bookseller in the first half of fifteenth century Florence, sold to the *élites* (intellectual as well as social and political) in Italy and in Europe. The first books printed in Florence were produced for and used by a popular readership assigning specific functionalities to different types of books, such as acquiring primary education through school books or engaging in religious devotion through reading devotional tracts. Production and consumption of popular books occurred in organized market systems of written communication built around the relationships between printers, publishers, peddlers and potential clients. In fifteenth-century Florence the print potentials were co-opted by other organized systems of communication. I illustrate this process of exaptation with two examples.

The first example refers to the system through which Savonarola intervened in the political-religious conflict in the last decade of the fifteenth century in Florence. Savonarola used the verbal sermon, an artifact with the generic function to express a message of religious or moral content, assigning it a specific functionality: to communicate his message of strong criticism of the morality of the church. Through his verbal sermons he entered into communication with the public who listened at him and, through the discussions that followed, indirectly

with a wider audience. In a city like Florence, with a strong tradition of popular participation in public life, around Savonarola's verbal sermons was organized a system of relationships through which the verbal sermons achieved the specific functionality assigned to them. In this organized system of communication, Savonarola intentionally used print in new ways. The sermons began to be transcribed by the Florentine notary Lorenzo Violi. The texts were reviewed by Savonarola himself, who intervened actively in editing his sermons' editions, also by adding illustrations in the text in order to reach a wide audience. Most editions of the sermons were published by the printer-publisher Bartolomeo de' Libri, some by the printer Francesco Bonaccorsi for the publisher Piero Pacini da Pescia, who, more than any other Florentine publisher at that time, included illustrations in the volumes he produced. In other words, Savonarola attributed to printed texts – an artifact with the generic functionality to communicate something in written form – the specific functionality he assigned to his verbal sermons, to communicate a particular message of strong criticism. The printed texts of the sermons perform this task through the system of relationships that author, printers, publishers and booksellers had with a readership that, in a city like Florence with a high level of literacy[10], was potentially larger than, but also different from, that able to attend the sermons.

The printed texts of Savonarola's sermons, in the form of short books or pamphlets, represent an exaptation of print intrinsic (or inherent) potentials. They derive from a new functionality attributed to print that generated a new system of relations between author, publishers, printers and readership. This exaptation process gave rise to a new type of book intended to intervene in the public life of the city, with a new and more direct link between author and the potential readership. It is important to emphasize that, as a result of this process, for a certain period two structurally different artifacts – the verbal sermons delivered in church and sermons as printed texts – meet, in two different organized systems of communication, at least in part the same functionality of communicating a particular message. This result represents a case of emerging degeneracy. When the verbal sermons of Savonarola were forbidden by the Pope, and during the period when Savonarola respected this prohibition, the circulation of printed texts of sermons was the only one of these communication systems in action. At that time, compared to verbal communication, printed texts provided additional features: they could be reproduced, stored, delivered and used in different places and times than those where they were originally produced. These features provided printed texts an impact very different from verbal communication. For example, Savonarola's sermons in their written version had an impact by no means restricted to Florence, or to Savonarola's lifetime. In a qualitatively different way and in a much larger scale this is true for Luther's published

sermons, which were the greatest publishing triumph of the first century of print and had the most far-reaching effects imaginable (Edwards, 1994).

The second example of exaptation and emerging degeneracy refers to the modalities in which print was co-opted by the communication system connected to the art of singing legendary stories in the streets and courtyards of Italian cities, well established since the thirteenth century[11]. Until the late fifteenth century, Florence was the home of the ballad singers, the city with the oldest and best consolidated tradition of this form of communication. Ballad singers performed in the square opposite the church of San Martino in the same street where the San Jacopo di Ripoli press was located. They sang legendary stories of the *chansons de gestes*, lives of saints and satirical sermons to an audience of listeners of all social classes.

The print potentials were co-opted by this oral communication system through the interaction between the ballad singers and the (new) printed artifacts. In Florence, printed texts were distributed not only through booksellers – who could also be editors and printers – but also through peddlers. Thus, the books were sold in the streets. The San Jacopo di Ripoli press, for example, used ballad singers and *ciurmatori*[12] to sell books. In this way ballad singers and *ciurmatori* came into contact with new artifacts – the printed text. This interaction had an unexpected outcome. Ballad singers and *ciurmatori* began to order printed texts of ballads and short stories of the traditional popular literature to the San Jacopo di Ripoli press[13]: they attributed a new functionality to print potentials and developed new products. These short printed texts, sometimes only a single sheet, are an exaptation of the inherent potentials of printing technology. As a result of this exaptation, the functionalities attributed by the users to the popular literature could now be achieved through two structurally different artifacts – ballad singers' performances and printed texts – provided by two different, but in this case adjacent, organized systems of communication.

In the above cases of emerging degeneracy, structurally different artifacts coexist providing functionalities that are not exactly the same but that overlap. For example, sung and printed ballads both delivered the possibility to enjoy the popular literature. However, the sung ballads delivered functionality not obtainable from the printed ones, in terms of the emotional and aesthetic pleasures tied to the collective experience of music. The printed ballads offered, instead, the functionality to read the legendary stories at different times and in places compared to when they were represented in the squares. This second way to make use of popular literature emerged in connection with the specific way of using this literature through the sung ballads. In others word, relationships around sung ballads and print potentials generated a new way to make use of popular literature, giving raise to a new functionality attributed to print ballads. Sung and printed

ballads coexisted by virtue of their specific but overlapping functionalities which, for a time, supported each other.

These examples show how the emergence of new types of books is the result of the process of exaptation and not, at least not directly, of the function for which the printing technology was "born," i.e. to reproduce texts in many copies. The specific functionalities attributed to the print intrinsic potentials generated different organized systems and different artifacts through which these specific functionalities became usable by producers and users. The relationship between exaptation and degeneracy considered so far can be summarized as follows. Several types of printed books, the result of exaptation processes, can live together with structurally different artifacts – such as verbal forms of communication or manuscripts books – which provide (at least part of) the same functionality. In this sense, exaptations generate degeneracy.

The processes of exaptation occur in conditions of ontological uncertainty. None of the new print artifacts, of the new agents and of the transformations in relationships between agents related to these processes were predictable. The key consideration here is that, under ontological uncertainty, agents act in constructing new products and new markets undertaking a series of interactions through which they orient their activities towards transforming particular zones of agent-artifact space[14].

Degeneracy makes possible further exaptation. In an organized system of relationships between producer, sellers and users, new functionalities and new artifacts can emerge. For example, when ballad singers and *ciurmatori* started selling books for the San Jacopo di Ripoli press, they relate with a particular readership and with a books' producer. From this relationship emerged their new activity of "publishers" of popular cheap books (which was joined to the pre-existing activity of verbal performances). Later, from this new activity emerged an innovation: ballad singers and *ciurmatori* began to use the songs and printed texts to offer the public not just the traditional popular literature but also interpretations and disclosures of contemporary events. In others words, they attributed a new functionality to verbal and print potentials and began to develop new products – songs, stories and related printed texts inspired by contemporary events – that they offered as singular or combined products (Novati, 1907 p. 99). These new products represent an exaptation triggered by degeneracy.

Fig. 1 summarizes the processes illustrated by these examples. At the microlevel, specific functionalities (F) are attributed to artifacts (A) structurally endowed with appropriate generic functionalities and hence potentially able to provide specific functionalities. At the mesolevel, artifacts to which have been attributed a specific functionality (FA) are developed in an organized system of interactions between producers, sellers and users. This organized system produces

outputs (O) providing the specific functionality. In these examples the specific functionalities (F_1) assigned to verbal expression (A_1) generated artifacts – critical verbal sermons or traditional ballads (F_1A_1) – that, through organized systems of interaction with the public, were able to provide the functionalities attributed to them by producers and users ($O_{1,1}$). When these functionalities were assigned to generic printed texts (A_2) potentially able to provide them in a new way, new artifacts were created in a new organized system: Savonarola's critical sermons or traditional ballads printed texts (F_1A_2 provided through $O_{1,2}$). In this way exaptations of printing intrinsic potentials generated different artifacts able to provide the same functionalities, i.e. emerging degeneracy is generated.

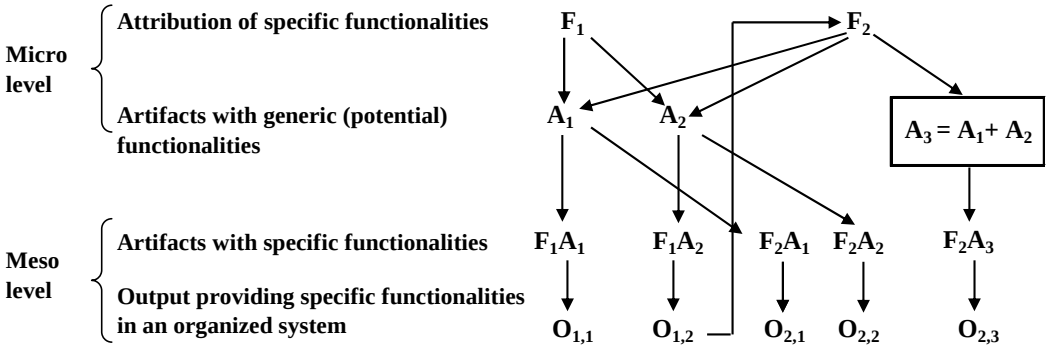

Fig. 1 An example of degeneracy emerging from exaptation and of exaptation triggered by degeneracy

Degeneracy triggered exaptations. The interactions between producers, sellers and users in an organized system have led to new functionalities (F_2) attributed to existing and new artifacts: in the second example the new specific functionality is to use the songs and printed texts to offer the public interpretations and disclosures of contemporary events. In this way new artifacts have been developed as exaptation of existing artifacts: songs and printed texts inspired by contemporary events and a combination of both artifacts (F_2A_1, F_2A_2, F_2A_3). At the same time, the degeneracy is increased: in different organised systems new outputs emerge to satisfy (at least part) the same specific functionalities ($O_{2,1}$, $O_{2,2}$, $O_{2,3}$).

6. Conclusions

Exaptation phenomena are common in innovation processes. In this article I focus attention on the theoretical foundations of these processes proposing a theoretical framework to analyze them.

On the theoretical ground I build on the idea that exaptation processes are essentially innovation-development processes through which an initial attribution of new functionalities to existing artifacts leads, in condition of ontological uncertainty, to new artifacts and new markets. To corroborate this idea I distinguish first of all between an adaptation and an exaptation perspective in innovation process. The *adaptation* perspective requires well defined technologies and products adopted for their function through a process of selection and variation. In this perspective, the historical origin of existing technologies and products should be inferred from their current utility. The *exaptation* perspective, by contrast, focuses on intrinsic but latent potentialities of existing technologies and products available for other uses provided that new functionalities are attributed to them. Exaptation phenomena require an analysis of their consequences. I draw attention, in particular, to the possible process by which an exaptation generates new artifacts and new markets apt to provide the new functionalities, in a path that leads from an initial exaptation to a subsequent process of "aptation".

To analyze the processes of exaptation in a market system I propose a theoretical framework founded on a nondeterministic ontology in which: (a) artifacts and markets are defined in terms of patterns of interactions between producers, sellers and consumers and (b) organization is defined in terms of different forms of coordination of interactions. In this framework the exaptation process is split in three fundamental steps, each characterized by a different level of coordination of interactions between users and producers. At the micro level, interactions between agents and artifacts give rise to attributions of functionality. At the meso level, recurring patterns of interactions emerge organized around individual plans of actions in consumption and production activities. At the macro level the consequences of the processes of exaptation on the whole system of relationships between producers and users should be considered. This requires an explicit re-coordination of production-consumption activity through conflict, negotiation, and sharing of common interests and systems of beliefs.

For a deeper understanding of the nature and implications of the exaptation process I introduce the complex links between exaptation and degeneracy, which is the property of structural different elements providing at least in part the same function. The historical examples used to illustrate this process suggest that emerging degeneracy increases the complexity of the system: the attribution of functionality previously provided by existing artifacts to new artifacts potentially able to provide them in a new way can generate new artifacts and new interacting agents. As a result of emerging degeneracy, structural different artifacts coexist providing at least in part the same functionality, or, more precisely, providing overlapping functionalities. Different structural artifacts coexist through their

specific but overlapping functionalities that contribute in this way to self-sustaining degeneracy. This type of degeneracy emerges from the interactions between agents and artifacts in the process by which the attribution of new functionality leads to new products. Relationships between agents around old and new artifacts give raise to new functionalities. So, emerging degeneracy makes possible new potential for further exaptation processes.

Exploring the complex links between exaptation and degeneracy open a wide range of possibilities in the analysis of innovation and development processes. Empirical research, for example, should uncover the links between new information and communication technologies and communication systems and technologies that already exist in providing new functionalities, new artifacts and new market systems. This is the case of the appearance of new electronic devices for presenting and reading books and newspapers, which in any case, at least for now, continue to be printed as well. In terms of policy implications, the links between exaptation and degeneracy discussed in this essay suggest that leaving open a number of technological systems can (potentially) foster innovation. Moreover, relevant theoretical issues may be addressed through modeling, a research development currently in phase of elaboration. In a companion essay with Marco Villani, the theoretical insights of this essay will be bolstered by using two agent-based models[15] focusing: (a) at the microlevel, on the possible conditions fostering exaptation examining the role of the quantity and quality of information exchanged between users and producers and the presence of noise and learning in the communication processes and (b) at mesolevel, on the effects of exaptation-innovation processes, examining the emergence of recurring patterns of interaction between agents and artifacts and the role of degeneracy in increasing diversity.

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Notes

1 I refer to Antonelli (2009) for an analysis of the economics of innovation from its classical legacies to the economics of complexity.

2 According to Alchian (1950) under uncertainty ex ante profit maximization cannot be a guide for business behaviour. Market mechanism operates, rather, through a natural selection mechanism that rewards firms most successful in terms of obtaining positive ex post profits.

On this point see also Friedman (1953), pp. 19-23. Penrose (1952, especially pp. 809-816) criticized Alchian, arguing that the presence of human intentionality makes the biological analogy inapplicable to the firm's and industry's growth. On the same point see also Richardson (1960, p. 140, note 1). For a wider critical discussion of the use of biological metaphors in economics see Ginzburg (2009).

[3] Nelson and Winter's theory is a selection theory of Lamarckian type in which replicating instruction set (the routines) can be intentionally modified (see Nelson and Winter, 1982 p. 11 for an explicit reference to Lamarckism of their theory). This possibility modifying the replicating instruction encoded in routines allows accommodating intentionality and knowledge growth in a socio-economic selection theory. Recently, Knudsen (2002) and Hodgson and Knudsen (2006) argued the necessity and inevitability of a generalized Darwinian theory on the basis of which to explain the intentionality and knowledge growth. So, according to these authors, the Lamarckian theory must be nested in a generalized Darwinian theory. On this subject I can not dwell here. See however Nelson (2006) and Hodgson and Knudsen (2007)

[4] On the non-derivability of the historical origin from the current utility in biological systems and in human institutions see Gould (2002), pp. 1215-1218, and Nietzsche (1887) quoted by Gould.

[5] On the distinction between micro, meso and macro see Dopfer, Foster and Potts (2004).

[6] For a discussion of Knight's concept of uncertainty see Langlois and Cosgel (1993). On the relationship between ontological uncertainty and Knight's notion of uncertainty see Lane and Maxfield (2005), pp. 9-10. On the relationship between uncertainty and exaptation see Bonifati (2010).

[7] See section 1.

[8] Sources of case studies reported below can be found in a broad and detailed study in Bonifati (2008), in particular chaps. 4, 8 and 10, pp. 81-94, 139-157 and 181-212.

[9] Bonifati (2010) argue that "this example reveals that "more is different": quantitative changes in scale of the potential production produce qualitative changes in the relation between production, technology and consumption" (p. 751).

[10] See Cipolla (1969), cap. 2.

[11] See Novati (1907), pp. 89-117, Bonifati (2008), pp. 143-145 e 186 and references herein.

[12] In the ancient meaning "ciurmatore" is every seller that sells cheap goods.

[13] See Conway (1999), pp.131, 195, and 225 and Bonifati (2008), p. 186.

[14] Lane and Maxfield (1997 pp. 194-195) define these relationships as generative and characterize them by the following five properties: (a) *heterogeneity*; (b) *aligned directedness*; (c) *mutual directedness*; (d) *permissions*; (e) *action opportunities*.

[15] Previous versions of these models can be found in Villani et al (2007) and Lane et al (2006).

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