MARIO COCCIA

# THE ECONOMICS OF SCIENCE AND INNOVATION: NEW DIRECTIONS

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# Preface

One of the most significant topics in economics and social sciences is to explain the active role that science and technological innovation play in the economic and social change of nations.

Firstly, the term innovation and science advances are used so widely to indicate something new and different. However, this definition doesn't tell us how we would recognize an innovation and science advances, how we could categorize them, how to explain their origin and evolution, as well as how to measure them in markets and society.

The goal of this book is to explain some characteristics of technological innovation and science in society. In particular, this book focuses on new researches that can clarify the origins of studies concerning science and innovation, the categorization of innovation, the sources and aspects of the evolution of innovation and some techniques to measure technological advances and predict which technologies are likely to evolve rapidly in society.

This book is designed for students, undergraduate, graduate or managers in business and public administration that wish to clarify critical concepts in the field of science and technological innovation and that wish to expand their knowledge on these subjects areas.

I have attempted to minimize the use of extremely complex theories and studies. Those that I include are integrated with examples and actual applications in economic, social and organizational settings. In order to attain a reasonable depth, this book concentrates on selected topics of particular relevance to problems of science and technology, and which meet the needs of the intended audience.

The book is divided in four interrelated parts.

- First of all, the chapter 1 of the book is an introduction to the methods of inquiry in social science.
- The first part of this book focuses on the origin of studies concerning economics of innovation and science.
- The second part contains a new approach to classify technological innovation considering the interaction between technologies. A vital theorem is stated to explain and generalize how technologies evolve over time and space.
- Part three of the book concentrates on sources of innovation and science in society, the role of disruptive firms in generating radical innovation and how types of government can affect innovative outputs of countries.
- The final part of the book explains some approaches to measure the evolution of innovation to support technology analysis and management of technology directed to foster technologies that are likeliest to evolve rapidly in society.

However, no single book could hope to cover adequately all aspects of what is wide and essentially multi-disciplinary field of inquiry, and it is not the intention to attempt to cover all aspects of science evolution and technological change. It is regrettable but inevitable therefore that some topics are excluded or given only limited coverage and it is not possible to meet fully the preferences of all readers. I hope that readers dealing with technological innovation and sociology of science, such as students and managers, policymakers, etc. are able to see this text as a starting point to understand the complex processes of science evolution and technological change in society.

This book’s strengths and weaknesses are the responsibility of author.

# Contents

# Introduction

Social scientists for over a century have recognized the complexity of the conceptual and methodological issues surrounding science and innovation, especially with respect to sources, evolution and measurement of technical change and evolution of science. In short, how do we identify manifold sources of science and technology? Are they the same factors that we can use to measure the evolution and diffusion? How science and technology evolve over time and space? In this book, I briefly examine these topics focusing on the development of some of critical aspects concerning the sources, evolution and related measurement of technological innovation and science in organizations and society (cf., Coccia, 2005, 2005a; 2010, 2010a, 2014, 2015, 2015a, 2018, 2018a, 2018b; Coccia & Wang, 2015, 2016).

In general, the concept invention and its relation to "science and invention" have varied considerably. Fagerberg (2005), for example, regards invention as the first appearance of an idea for a new productor process, whereas innovation represents the first attempt to put it into practice, which may occur considerably later. Moreover, innovation may be seen not as a "one-off" but as a continuing accumulation of changes. Barnett (1953, pp.7-8) regards inventions as physical things, whereas an innovation is defined as: "any thought, behavior or thing that is new because it is qualitatively different from existing forms". The distinction made by Elster (1986) in his study of technical change corresponds closely to that advocated by Fagerberg: innovation is "new technical knowledge" (p.93) and invention is the generation of a new idea. Elster (1986) also points out that diffusion often involves innovation, as modifications to a product or process are made in response to a new context, whereas substitution, making a change in some process using existing technical knowledge, also easily shades into innovation. Schumpeter (1934) argued that: "[Innovation] is that kind of change arising within the system which so displaces its equilibrium point that the new one cannot be reached from the old one by infinitesimal steps. Add successively as many mail coaches as you please, you will never get a railway thereby" (Schumpeter, 1934, p.64). Schumpeter (1934) also gave a role to adaptive technical change and the importance of the accumulation of small changes over time (cf., Elster, 1986). Whether such innovations, small and incremental or large and discontinuous, will be successful is another matter again and depends on the various selection and environmental processes (cf., Coccia, 2005, 2005a, 2016).

In general, the importance of studies in science and technology is due to their contributing role for supporting economic growth and employment of nations. Scholars have generated a vast literature and inquiries focusing on economics of science and technology. Although it is sometimes forgotten, much of what we take for "modern" perspectives and new directions are actually built to varying degrees on decades of thoughtful research by previous scholars. The purpose of this book is to provide the scholarly foundations for the science and technology analysis focusing on critical aspects of science and innovation in a multidisplinary perspective described by following sections (cf., Coccia, 2017, 2005b, 2010b, 2010c, 2011, 2014a, 2014b, 2014c, 2014d, 2015b, 2017a, 2017b, 2018c, 2018d, 2018e, 2018f, 2018g, 2018h, 2018i, 2018l, 2018m, 2018n, Coccia & Cadario, 2014, Coccia & Rolfo, 2010).

## Historical perspective of studies on science and innovation

In the first paper of this section, innovation is explained considering the nineteenth-century writings of philosophers that viewed the production of novelties—new ideas, new ways of doing things, and the like—as the underlying evolutionary force that propels economies and cultures up the ladder of cultural complexity. In fact, studies of the economics of technical change go back to many years before Schumpeter's contributions. The Scottish philosopher John Rae with his book "Statement of Some New Principles on the Subject of Political Economy", issued in 1834, put forward the foundations of the economics of innovation individuating the nature, causes of technological innovations and effects of technological progress on economic growth of nations. Rae also discusses the evolution and role of vital technologies for the wealth and employment in Europe and North America. Rae's work, discussed here, is basic for understanding the origin of the Economics of innovation, for defining the domain of this discipline and for explaining the effects of vital technologies in society.

In addition, this section explains a new discipline that analyses the role of science in society: the economics of scientific research. It investigates the origins, nature, evolution and structure of the scientific research. One of the first scholars that has tried to systematize this discipline of the economics of scientific research is Paul Freedman. This study endeavors to show whenever possible the evolution of this discipline through central topics that explain the nature of this research field for human progress.

## Classification and evolution of innovation

The first article in this section suggests a new categorization of innovations to support technology analysis and to explain the evolution of innovation. In particular, this study here categorizes innovations considering the taxonomic characteristics of interaction between technologies in complex systems. The proposed classification, in a broad analogy with the ecology, includes four categories of technology considering the type of their interaction: 1) technological parasitism is a relationship between two technologies A and B in which A benefits from the interaction with B, whereas B has a negative side from interaction with A; 2) technological commensalism is a relationship between technologies where technology A benefits from B without affecting it; 3) technological mutualism is a relationship in which technologies A and B benefit from the activity of the other; finally, 4) technological symbiosis is a long-term interaction between A and B technologies that generates coevolution in complex systems. This classification can predict evolutionary pathways of technologies and explain patterns of technological innovation in society. This approach begins the process of clarifying typologies of interactive technologies that explain the long-run evolution of technology. The theoretical framework can be a ground work for development of more sophisticated theories to clarify technological and social change.

Moreover, to clarify the evolution of technology, the second article proposes the theorem of not independence of any technological innovation that in the long run, the behavior and evolution of any technological innovation is not independent from the behavior and evolution of the other technological innovations.

In particular, any technological innovation does not function as an independent system per se, but each innovation depends on the other technological innovations to form a complex system of parts that interact and coevolve in a non-simple way. This theorem of not independence of any technological innovation can explain and generalize, whenever possible, one of the characteristics of the evolution of technology that generates technological and economic change in human society.

## Sources of innovation

In this section, a first study explains the fishbone diagram for technological analysis. Fishbone diagram (also called Ishikawa diagrams or cause-and-effect diagrams) is a graphical technique to show the several causes of a specific event or phenomenon. In particular, a fishbone diagram (the shape is similar to a fish skeleton) is a common tool used for a cause and effect analysis to identify a complex interplay of causes for a specific problem or event. The fishbone diagram can be a comprehensive theoretical framework to represent and analyze the sources of innovation. Fishbone diagram is applied here as a novel graphical representation to identify, explore and analyze whenever possible, the potential root causes of the source and evolution of General Purpose Technologies (GPTs). In particular, fishbone diagram seems to be an appropriate and general technique of graphical representation to explore and categorize, clearly and simply, the potential root causes of the evolution of technological innovations for an appropriate management of technology.

Another chapter in this section focuses on the aspects that induce nations to produce science and technology. Firstly, the concept of science is defined as a process that discovers the root causes of phenomena to explain and predict them in a context of adaptation of life to new economic and social bases, whereas scientific research is defined as a systematic process, applying methods of scientific inquiry, to solve consequential problems, to satisfy human wants, to take advantage of important opportunities and/or to cope with environmental threats. This study shows that scientific research reflects social climate in which it is carried out and it is driven by social and economic interests of nations to achieve power, wealth creation, technological superiority, productivity growth, etc. A main implication of this study is that scientific research is performed by nations to take advantage of important opportunities and/or to cope with environmental threats, such as in conflicts (economic, military, political, social, etc.). The empirical evidence of this study seems in general to support the sources of scientific research described. However, these conclusions are of course tentative. There is need for much more detailed theoretical and empirical research into the relations between science, society, economy and historical motivations.

Another chapter in this section investigates the competition between basic and applied research within public research organizations directed to produce science and new technology. International publications are considered here a proxy of basic research, whereas self-financing deriving from technology transfer activities is an indicator of applied research and new technology. Results suggest, within one of the largest European research organizations, an increasing competition between basic and applied research, both in human and natural sciences, likely due to shrinking of public research lab budgets. In particular, current institutes and scientists pay more attention to applied research activities, which are capable of attracting market funds for economic survival of public research labs but this organizational behavior reduces basic research activity in the long run. Managerial and organizational implications for R&D of public research organizations are also discussed.

In order to explain the manifold sources of innovation, another chapter clarifies the differences of technological performances among nations. In particular, the paper analyses the relation between type of government of nations, and their technological and socioeconomic performances. Results suggest that high levels of technological performance of nations seem to be associated with executive based on parliamentary monarchy and monarchy, whereas nations with mixed executive tend to have lower innovative outputs. A possible reason is that, in general, some typologies of executive (e.g., Monarchy) support the political stability of countries with fruitful socioeconomic and historical paths of developmental over the long run. Overall, then, the structure of executives of nations may be one of contributing factors to explain dissimilar patterns of technological performances and economic growth of nations over time and space.

Another main driver of science and innovation discussed in this section is disruptive firms: they are firms with market leadership that deliberate introduce new and improved generations of durable goods that destroy, directly or indirectly, similar products present in markets in order to support their competitive advantage and/or market leadership. These disruptive firms support technological and industrial change and induce consumers to buy new products to adapt to new socioeconomic environment. In particular, disruptive firms generate and spread path-breaking innovations in order to achieve and sustain the goal of a (temporary) profit monopoly and industrial leadership. This organizational behavior and strategy of disruptive firms support technological and social change in society. This study can be useful for bringing a new perspective to explain and generalize one of the determinants that generates technological and industrial change. Overall, then this study suggests that one of the general sources of technological change is due to disruptive firms (subjects), rather than disruptive technologies (objects), that generate market shifts in a Schumpeterian world of innovation-based competition.

## Technometrics

The final part of the book explains some approaches of technometrics, which is a discipline that measures and evaluates technological change with important policy implications. Technometric approaches, initiated in the 1950s, with the pioneering researches carried out by the scholars of RAND Corporation (Coccia, 2005, 2005a). In the second half of the twentieth century, technometrics becomes a distinct field of investigation, characterized by the coming together of several disciplines, such as econometrics, engineering and applied mathematics, mathematical and multivariate statistics, and so on.

A simple model of the development of technology is presented here to measure main technological advances. This model, in a broad analogy with evolutionary ecology of parasites, within a theoretical framework of Generalized Darwinism, can measure and explain vital characteristics of technological advances and technological evolution. In particular, the evolution of technology is modelled here in terms of morphological changes between a host technology and a main subsystem of technology (parasitic technology). The coefficient of evolutionary growth of this simple model here indicates the grade and type of the evolution of technology. This coefficient is quantified in real cases study using historical data of farm tractor, freight locomotive and electricity generation technology in steam-powered plants and internal-combustion plants. The approach of measurement and assessment of technological evolution proposed here seems to be appropriate in grasping the dynamics of technological evolution to predict which technologies are likeliest to evolve rapidly.

Another study here measures and analyzes the driving technical characteristics in a specific product innovation to predict technological trajectories, using hedonic price method and other approaches. This approach is applied on empirical data of smartphone technology. Results show technological trajectories supporting the evolution of smartphone technology. In particular, critical characteristics of technological evolution in smartphone technology are: RAM in Gigabyte (Gb), 1st and 2nd camera in megapixels, memory in Gb and resolution in total pixels. Finally, implications of innovation product management are discussed.

Overall, then, the studies presented in this book show that origin and evolution of science and technology are due to manifold factors that guide long-run pathways of development in society (Basalla, 1988). Technical change and science evolution, then, become a key area of analytical focus in any study of society, especially with respect to the form of different inventions and technological innovations, their composition, and process of science and technological evolution supporting economic growth. Finally, it is one thing to know how and under what conditions innovation and science are transmitted, but it is a different matter to understand and explain where they came from and how to measure them. This book endeavors to clarify these challenges in the inter-related research field of science and technology.

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# 1. An introduction to the methods of inquiry in social sciences

We understand science today, it is important to understand its methods of inquiry. Such models indicate how the future of scientific fields can be investigated and developed. Methods of scientific inquiry generally aim to obtain knowledge in the form of testable explanations that scientists can use to predict the results of future phenomena in nature and society (Popper, 1959). In particular, main elements of the methods of inquiry in a hypothetic deductive view are: a) observation and accurate measures of the subject of scientific inquiry; b) hypothetical explanations of the subject of inquiry; c) controlled experiment for testing the hypotheses; d) prediction. Next sections, will trace the development of methods of inquiry based on scientific thinking of rationalism and empiricism, the first two major (and opposed) philosophies of science. Subsequently, a synthesis of these conflicting positions by Kant is discussed. After that, it will be traced the development of the major contemporary theories of methods of scientific inquiry: the speculative metaphysical, the positivistic, and the pragmatic (cf. Kaplan, 2009; West Churchman & Ackoff, 1950).

# Development of the methods of scientific inquiry in the philosophy of science

## Rationalism: The role of reason in science

The school of rationalism argues that the development of reason is a basic faculty in the method of inquiry. In this approach, the Greek mathematicians had the purpose to systematize the general properties of space (i.e., geometry).

Reason was a faculty that had two fundamental features: it provides information concerning the essences of things, and it shows how to go from these essences to other characteristics of the world. Reason provides "clear and distinct" ideas, and guides to the conclusions from such ideas. The history of science and philosophy seems to show that it is no easy matter to identify the clear and distinct ideas. Leibniz attempted to overcome this difficulty by making analytic statements the beginning point of rational inquiry that cannot be denied without violating the Law of Contradiction. A problem in this approach is to connect pure formal defining to reality marked a turning point in man's thoughts on the correct process of scientific inquiry. Some contemporary scholars have attempted to use rational methods of inquiry in some scientific fields, but the modern rational method does not always provide truth. However, speculation and the clear use of reason are essentially the only methods at scholar's disposal in certain areas, such as religion, morality, and metaphysics (West Churchman & Ackoff, 1950).

## Empiricism: The role of observation in science

The priority of reason was questioned and attacked by the empiricism that replaced reason by sensation as the source of all knowledge. Locke made the first comprehensive and systematic attempt to do this. Starting from simple ideas, and with the aid of the mental operations of compounding, relating, and abstracting, he sought to show how other facts (ideas) could be derived. He also tried to show how knowledge of general propositions should be derived by the process of comparing ideas. This approach by Locke was seriously challenged by the later philosophers who accepted his general program.

Berkeley and Hume showed that many ideas which appeared simple to Locke, were actually not so, and consequently they raised the problem of the adequacy of intuition or introspection as a criterion of simplicity. Locke's notion of a mental faculty of abstraction was refuted by Berkeley, who claimed that the mind can only perform generalizations, not abstractions, whereas Hume discards the faculty of generalization. Berkeley eliminates Locke's material substance, and bases all reality in mental substance. Reid and Hume show that not even the existence of a mental substance can be proved on empirical grounds. Hume also demonstrated our inability to assert any causal connections with certainty. Hence, knowledge is replaced by belief: the empirical analysis can only show with certainly our impressions.

## A synthesis of reason and observation by Kant

Kant shows that both sensory observation and general understanding are essential for meaningful experience. It is true that there is something given in sensation (the sensuous intuition), but in addition to the sensuous intuition, Kant argues that both space and time are a priori forms of experience, which are necessary to individuate objects. In this approach, the mind must bring to its experience a principle of regularity. That is, the natural world is well ordered because this is the manner in which the mind makes understandable its sensuous intuitions.

## Modern rationalism: The speculative method

Rationalism since Kant has turned from the rigorous method of deductive science. The newer rationalism shares with the old the belief that the mind can intuitively grasp truth; but for the newer rationalism, truth comes only at the end of the process, and very tentatively. Rational or metaphysical truth, in short, is derived by a process in which the generalizations come out of rich experience, but are not themselves mere mechanical inductions or deductions, but creative acts of the mind. For Hegel, the process was dialectical, proceeding from conflicts and working up by successive syntheses to some higher and richer stage. For Bergson, the process is intuitive. For Hall, it is imaginative insight. Finally, the modern rationalist claims that his method is in some sense basic to all others, and that other methods must always make metaphysical, or ethical assumptions that can only be justified by rational insight, intuition, faith, and the like.

## The positivistic method

The development of the contemporary analysis of scientific method, called "logical positivism”, is due to Hume with an attack on speculative metaphysics, which became the cornerstone of Comte's positive philosophy. Comte attempted to demonstrate that metaphysical thinking represented an intermediate historical stage through which man passed on his way to the full maturity of positive or scientific thought. Further, he constructed a hierarchy of sciences based on the temporal order and logical simplicity in the appearance of the special scientific disciplines. This notion of a hierarchy appears in new guise in logical positivism, as the theory of physicalism. In this approach, Mill attempted to show how by designing experience, causal connections could be established on purely empirical grounds. Mill, in effect, defined the problem of "inductive logic". Finally, Mach and Pearson conceived of law as an economic measure, a way of summarizing past experiences and of indicating expectations. Laws were not taken as irrefutable, exact, or as representing necessary connections in nature. They were merely taken as provisional cataloguing instruments.

## The method of logical positivism

Logical positivism is a new empiricism, which unlike its predecessor, uses logical rather than psychological analyses as an instrument for the study of scientific method. It takes the understanding of language in terms of its form (syntax), content (semantics), and uses (pragmatics) to be basic to an understanding of methodological problems. It attempts to show how language construction can take place from a basic set of elements and rules. Such a language can be considered quite apart from any factual meaning. Meanings are fundamentally assigned by means of linguistic rules referring ultimately to protocol statements, which are more or less directly verified in experience. Explanation and prediction can then be given precise definitions as aspects of scientific method.

## Modern synthesis: The pragmatic method

Science, in the pragmatic approach, is conceived, not in terms of what it actually does, but in terms of its aims. In the pattern of inquiry (due to Dewey), the emphasis is on the resolution of an indeterminate situation into a determinate one. The idea is that facts and concepts are instruments for certain types of action, and have no meaning apart from this context.

In order to consider the meaning of science in a more precise sense, pragmatism introduces the distinction between goals (which are presumably attainable objectives) and ideals (which are unattainable but approachable within any limits). The ideal which defines science is that of finding perfect means for any end in any situation. In so far as activity furthers man in his struggle for this ideal, it is scientific. A classification of sub-ideals represents steps in the pattern of science's progress that must be approached as science itself progresses.

Finally, pragmatism's attitude toward metaphysics and positivism is that they represent partial (and often fruitful) methods, none of which are final in themselves.

## General models of inquiry

Considering the philosophies of science discussed above, models of scientific inquiry can be classical, pragmatic and logical empiricism approaches:

* The classical model of scientific inquiry derives from Aristotle, who distinguished the forms of approximate and exact reasoning. A common distinction in science is between logical paths of induction and deduction. The etymology is from the Latin verb *ducere*, to draw on or along, to lead, and with the Latin propensity for prefixes. With the prefixes *in* and *de*, meaning ‘in’ and ‘from,’ respectively, both words may have many meanings. Simply, *to induce* could mean ‘to lead or draw into, to infer, to persuade,’ and *induction* is ‘to lead to the conclusion’. *To deduce* could mean ‘to lead from, to draw from’ and *deduction* is ‘to draw a conclusion from’. Both terms define systems of logic with the purpose of solving problems.

*Deductive methodof inquiry* is based on deduction: “inference by reasoning from generals to particulars,” or “the process of deducing from something known or assumed”. Deductive reasoning, also deductive logic, is the process of reasoning from one or more statements (premises) to reach a logically certain conclusion. Put otherwise, deductive reasoning goes in the same direction as that of the conditionals, and links premises with conclusions. If all premises are true, the terms are clear, and the rules of deductive logic are followed, then the conclusion reached is necessarily true. Deductive reasoning (top-down logic) contrasts with inductive reasoning (bottom-up logic).

*Inductive model of inquiry* starts by doing experiments and then derives theories from the data. This process collects data and then move to theoretical implications. Scholars are involved in a continuous loop of data collection and theory formation. Problem solving in scientific fields leads to a diversity of induction: formation of hypotheses (HPs), the need to test HPs supports the study design and controlled experimental activity: experiments, in turn, can generate consequential problems to be solved, which lead to new hypotheses and further science advances (e.g., in medicine the study of mutant cancers; cf., Coccia, 2016). Induction is riskier than deduction because it can lead to conclusions that may be uncertain. Overall, then, while the conclusion of a deductive argument is certain, the truth of the conclusion of an inductive argument may be probable, based upon the evidence given. Inductive reasoning can be a derivation of general principles from specific observations, though some sources disagree with this usage.

* Pragmatic model by Charles Sanders Peirce (1992) characterized inquiry a ‘struggle’ to replace doubt with ‘settled belief’. The method of science is an experimental method, and the application of the pragmatist maxim reveals how hypotheses can be subject to experimental test. Dewey's conception of inquiry, found in his *Logic: the Theory of Inquiry* is to understand a problem through describing its elements and identifying their relations. Identifying a concrete question that we need to answer is a sign that we are already making progress: ‘the controlled or directed transformation of an indeterminate situation into one that is so determinate in its constituent distinctions and relations as to convert the elements of the original situation into a unified whole’ (Deway, 1938, pp.104-105). As Smith (1978, p. 98) has put it: ‘Peirce aimed at “fixing” belief, whereas Dewey aimed at “fixing” the situation.’ Peirce calls his pragmatism "the logic of abduction".

Abduction by Peirce is based on simple visualization of phenomena. In fact, many visual stimuli are impoverished or ambiguous, people are adept at imposing order on them, creating hypotheses to explain what has been observed. Hence, abductive reasoning (also called abduction, abductive inference, or retroduction) is a form of logical inference which starts with an observation then seeks to find the simplest and most likely explanation. In abductive reasoning, unlike deductive reasoning, the premises do not guarantee the conclusion. Abductive reasoning is an inference to the best explanation, although not all uses of the terms abduction and inference to the best explanation are exactly equivalent.

* Logical empiricism is based on a set of axioms in formal deductive systems. Theories are confirmed by deducing their effects from axioms and checking to see whether the predictions hold; this model of inquiry is called hypothetico-deductive because it uses the hypotheses to make predictions, rather than the derivation of laws from observations, similarly to earlier empiricism (Hempel, 1965). Put otherwise, scholars with hypothetico-deductive method of inquiry state hypotheses and then do experiments to test them. In most scientific fields, the hypothetico-deductive method of scientific inquiry by Popper is the dominant model of inquiry. The approach by Popper (1959) was hypothetic deductive, however he saw the critical role of prediction to be the attempt to falsify theories, not to confirm them (cf.,

Thagard, 1993, p.192ff). For instance, in psychology and other social sciences, scholars state a hypothesis underpinned in a theoretical framework, then describe the materials and experimental methods, results achieved and finally discuss how experimental results bear on the initial hypothesis for possible predictions. This approach can generate distortion of the process of inquiry because it may be possible to form a sharp hypothesis and then test it with empirical evidence. The general hypothetico-deductive scheme can be synthetized in figure 1.

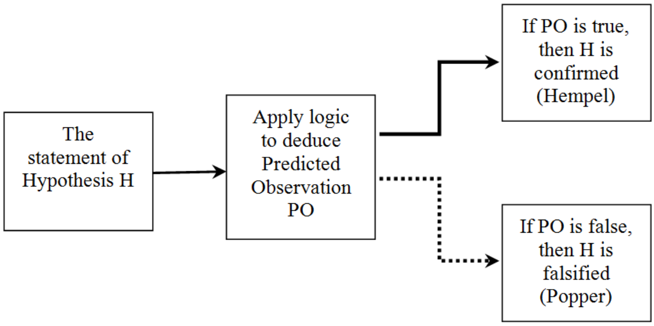


**Figure 1.** *Hypothetico-deductive scheme. Adapted from Thagard (1993, p.192).*

Hanson (1958) criticized this model of inquiry because theory and observation were much more intertwined. Scientific realism argues that science is not restricted to observable facts but knowledge can be achieved of what is not observable.

* Finally, analogy has a vital value in the evolution of science because the solution of problems in one scientific field—source domain — can be used for solving and explaining problems in another scientific field -target domain (Oppenheimer, 1955).

## Specific methods of inquiry in social sciences

In the general background of the models of inquiry just mentioned, some specific methods in social sciences are as follows.

### Game theory

Among the social and human sciences a method of inquiry is the game theory. A "game" is any activity with the structure of a contest, in which what one player decides to do, simultaneously or not simultaneously, depends on what it expects to be done by the other players. The specific content of the actions involved is irrelevant; all that matters is the payoff to the players associated with each possible combination of moves by the two sides. In this way utility theory also enters into the analysis. The game model thus serves for a wide variety of decision-making behaviour, particularly where it is supposed that a rational choice is done among alternative strategies of action. Accordingly, it has been applied to economic bargaining, political negotiation, the conduct of war, battle of the sexes, etc. Characteristic of game theory is the application of probability considerations to the choice of strategies. What is especially remarkable about this class of models of inquiry is that the mathematics used is essentially so elementary, while the behaviour to which the models usefully apply is complex (Watson, 2002).

### Multi-agent programmable modelling environment with NetLogo

NetLogo is an agent-based programming language and integrated modelling environment. The NetLogo environment enables exploration of complex phenomena. It comes with an extensive models library including models in a variety of domains, such as economics, biology, physics, chemistry, psychology, system dynamics. NetLogo allows exploration by modifying switches, sliders, choosers, inputs, and other interface elements. NetLogo is in use in a wide variety of scientific fields (Railsback & Grimm, 2011).

### Experimental approach in social science

It is a research method that aims to contribute to the understanding of human behaviour by means of controlled laboratory experiments (Vernon Smith, 2008). Data collected in experiments are used to estimate effect, test the validity of theories, and explore market mechanisms. Experiments usually use cash to motivate subjects, in order to mimic real-world incentives. Experiments are used to understand how and why markets and other exchange systems function as they do. Experiments may be conducted in the field or in laboratory settings, whether of individual or group behaviour. Variants of the subject outside such formal confines include natural and quasi-natural experiments.

### Counterfactual methods of causation

Counterfactual method of causation is that the meaning of causal claims can be explained in terms of counterfactual conditionals of the form "If *A* had not occurred, *C* would not have occurred". While counterfactual analyses have been given of type-causal concepts, most counterfactual analyses have focused on singular causal or token-causal claims of the form "event *C* caused event *E*'. The best known counterfactual analysis of causation is Lewis's (1973) theory. However, intense discussion over forty years has cast doubt on the adequacy of any simple analysis of singular causation in terms of counterfactuals. Current studies have seen a proliferation of different refinements of the basic idea to achieve a closer match with commonsense judgements about causation (Collin *et al.,* 2004).

### Multiple Working Hypotheses

The method of multiple working hypotheses (MWH) involves the development, prior to our research, of several hypotheses that might explain the phenomenon under study (Chamberlin, 1897). Many of these hypotheses will be contradictory, so that some, if not all, will prove to be false. However, the development of multiple hypotheses prior to the research allows us avoid the trap of the ruling hypothesis and thus makes it more likely that our research will lead to meaningful results. Hence, MWH method suggests all the possible explanations of the phenomenon to be studied, including the possibility that none of explanations are correct and the possibility that some new explanation may emerge. The method of multiple working hypotheses has several beneficial effects because a phenomenon is the result of several causes, not just one; the method of multiple working hypotheses also analyses the interaction of the several causes. The method also promotes much greater thoroughness than research directed toward one hypothesis, leading to lines of inquiry that scholars might otherwise overlook.

The method of multiple working hypotheses can have drawbacks. One is that it is impossible to express multiple hypotheses simultaneously, and thus there is a natural tendency to let one take primacy.

## Conclusion

Methods of inquiry consider that science advances are essentially due to individual scientists who solve problems, form hypotheses, and do controlled experiments. However, modern science is more and more performed by communities of scholars with international collaboration (Coccia & Wang, 2016). The modern methods of inquiry include many phases in the process of scientific research: study concept, study design and working hypotheses formation, acquisition of data, experiments, analysis and interpretation of data, drafting manuscripts, statistical analyses, critical revision of the project for important intellectual content, obtained funding, administrative, technical and material support and supervision. These complex phases can be distributed across individuals and/or communities of scientist worldwide (e.g., in medicine, astronomy, etc.). Overall, then, modern science is based on a variety of models of inquiry: some scholars focus on history, others on logical analyses, some continue to apply empiricism and state that science advances are concerned with truth only with respect to what can be observed. In general, scientific discovery in modern research fields is multifaceted, requiring diverse processes for generating concepts, for creating new hypothesis and performing controlled experiments. In conclusion, induction, deduction and other methods of inquiry are usually different approaches but never contradictory, often they are complementary tools that facilitate problem solving and knowledge creation within and between research fields.

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# 2. The origins of the economics of innovation

## Introduction

The economics of innovation is a fertile and rather recent specialization field within the economic theory. Around the mid-20th century it emerged as a distinct research field born of the coming together of different topics such as industrial organisation, sociology, history of technology, firm theory, management of technology and so forth. The interaction with other sciences, such as biology, physics, cognitive psychology, information theory and mathematical statistics has been a constant stimulus for this branch of economics.

This article aims at throwing light on the origins of the economics of innovation. After a brief description of the contributions made by economists of the 1800s, a period called by some authors pre-Schumpeterian (Grandstrand, 1994), the essay shall focus on the work of an author who is not very widely known among scholars of this branch of literature: J. Rae (1834; Ferrara, 1856; James, 1965; Coccia, 2005).

In the 19th century, when analysing economic phenomena, several scholars did not talk explicitly about innovation but such a concept can be drawn from the references they made to terms like science, technology, invention, machines and so forth. Among the economists before Smith, i.e. the Physiocratic and the Mercantilist scholars, references to technology were scarce and haphazard (Roll, 1954). Nevertheless, some economic ideas concerning technology did already exist. For instance, the idea that a temporary monopoly could serve as economic incentive in order to generate technical inventions was clearly expressed for the first time in the "Statute of Monopolies" in England in 1623. Francis Bacon (1561-1626) believed in the power of science to better economic conditions and standards of living. Before Bacon (and Galileo Galilei) the connection between science and practical activities was clouded by a religious and philosophical system of thought that aimed at achieving the salvation of the soul. In his book, *New Atlantis* Bacon (1629) addressed issues concerning the first basic concepts of what was later to be called the economics of innovation. Smith (1776) claimed that the specialization and division of labour produced an increase in the skills of workers, allowed for a save in time and for the introduction of new pieces of machinery. While Bacon considered science, technology, politics, industry and religion as deeply interrelated activities, Smith attributed to the economic sphere self-regulating characteristics, influenced by technology but ruled by an invisible hand. In the chapter on machines, Ricardo (1817) referred to technology that lessens workload. In Granstrand's opinion (1994), the scholar who before all others dealt with the interpretation of the economics of technology was Babbage (1791-1871) in his book *On the economy of machinery and manufacturers* dating back to 1832. Granstrand claims that, even though this work from 1832 has nowadays been forgotten, it could be to industry and technology economists what Smith's book has been to economics in general. Marx (1890; 1975) instead is usually claimed to be the first scholar who explicitly dealt with technological change from a macroeconomic point of view. In fact, he analysed innovation as a social process and its relationship with capital and labour that can generate class struggle and distribution problems. Another scholar who investigated the field of technology was Veblen (1899; 1904), who emphasised the importance of machinery and of engineers as a class (the relevance of the engineering profession was recognised also by Auguste Comte who considered engineers as a connecting link between science and technology). Veblen was also in favour of an evolutive approach in economics and stated this when economics started to set the paradigms of the neo-classical school (Marshall, 1890).

Considering the 1900s, Schumpeter (1939) is the first scholar who analysed the role of innovation in modern economies in a systematic manner. His distinction between invention and innovation is well-known and such a distinction points out that an invention is the creation of new knowledge regardless of its actual utilisation, while innovation must be regarded as the actual utilisation of knowledge for production purposes in order to do, in the economic field, *things differently*, according to his famous expression. The economist from Harvard also analysed the effects of innovation on firms, sectors and markets and his stance in relation to monopolies is especially renowned (Schumpeter, 1911; 1942).

The purpose of this research is to throw light, as already stated above, on the origins of the economics of innovation and, from this point of view, it aims at examining in greater depth the contribution given by the economist-philosopher, John Rae (1796-1872), who in his work dating back to 1834 provided a detailed analysis of the causes of inventions and of their effects on mankind, on the environment and on the economic growth caused by their accumulation.

The idea of studying Rae's contribution originated from remarking that in the history of economic thought on innovation, especially in Italy, references to the economist Rae are scarce, while the writer of this paper believes he played a fundamental role in establishing the paradigms of this branch of economics. The Italian scholar who gave the most consideration to Rae was Ferrara (1856), who included Rae's works in volume XI of the Bibliotecadell'Economista (the Economist's Collected Works), after his curiosity had been raised by a quote by Stuart Mill (1848). The Italian economist considered Rae's works worthy of inclusion in his Collected Works, despite the fact that these had escaped Mac Culloch's investigation and were excluded from *Literature of Political Economy*. Besides rediscovering the significant role of the Scottish philosopher in the birth of the economics of innovation, this article aims at trying to deduce from Rae's works a definition of this branch of economics, integrating it with later works on innovation in order to single out its structural characteristics and scientific purpose.

Rae's life and works will be described below (section 2) with specific reference to his attacks against the theory of free trade contained in Adam Smith's book *The wealth of nations* and to what some economists and historians have stated about him, in order to give him his rightful place in the history of economic thought. Section 3 will focus on the author's analysis of the inventive activity since this analysis anticipated several concepts that were later developed within the economics of innovation. This section will also attempt to provide a definition of economics of innovation by drawing from some concepts included in Rae's work. A further discussion and some concluding remarks complete the research.

# John Rae and the theory of nature and laws of capital

John Rae, an Scotsman born in Aberdeen on the June, 1st 1796, graduated from the University of Aberdeen and later attended the faculty of medicine at the University of Edinburgh without completing his studies. In 1822, he emigrated to Canada where besides teaching he also worked as a doctor. After a period in Canada, he moved to California and then to the Hawaiian islands of Maui, where he practiced a fruitful teaching activity. Later he went to live in New York City where he died on the 12th of July 1872 (Eatwell *et al.,* 1987; James, 1951; Website The History of Economic Thought, 2004). Rae is remembered for his book issued in 1834 *Statement of Some New Principles on the Subject of Political Economy in* which he attacked Smith's theories and put forward his own sociological capital theory. Rae's theory on capital had a strong influence on the entire Austrian school (Roll, 1954) whose main representatives were Menger, Wieser and Böhm-Bawerk (1900; Mixter, 1897; 1902). The first drew conclusions concerning the theory of value-utility, the second worked on the theory of cost and distribution and the latter on the theory of capital and interest. Rae did not possess a wide knowledge of other works concerning the field of economics and developed several of his concepts autonomously. He stated that the nature of wealth in general and the laws that determine its increase and decrease must be considered the true object of philosophical investigations, i.e. the subject matter of studies carried out by economists. According to Rae, Smith's book contained two mistakes: 1) the purpose of a true economist is to investigate the ultimate nature and causes of national wealth, but such an investigation was neglected in his book; 2) Smith used the results of laws as if they were laws themselves, thus exchanging effects with causes. Rae claimed that while writing his work Smith had not followed Bacon's philosophy on induction.

After having considered Smith's mistakes, Rae set himself the goal of describing the true nature and cause of wealth of nations and of the way in which it increases and decreases. His book is divided into three volumes (or three books according to the terminology he adopted). In the First Book, he tried to demonstrate how some principles similar to those used in *The wealth of nations* could be the strongly objected. In the Second Book, he analysed the nature of wealth and the laws that control its increase and decrease. Finally, in the Third Book, he described the practical application of his doctrines and principles.

Dorfman (1966) placed Rae among American Northern Protectionists because he was a great supporter of financing and subsidies to new-born firms and believed that legislators should support the progress of science and technology (*art* according to Rae's terminology). The funds could be taken from duties on the importation of luxury goods that, in Rae's opinion, would reduce lavishness and encourage saving. At first, the book was meant to be published in England but then Alexander Everett pushed him to publish it in Boston, also because there was a reduced rate in the State of New York. Everett explained his decision with the fact that the language was too technical and did not lean very much towards the protectionist cause. In actual fact, Rae's book was well written and could be used as a textbook for university students but it met with little success because the true obstacle it had to face was the fact that many did not consider luxury as a downfall, besides the opposition to Smith's theories who was very well-known in the English-speaking world.

In his book *History of Economic Analysis* Schumpeter (1954) drew attention above all to Rae's chaotic life saying that "*…a nervous sensibility made him a failure at everything he touched…*" (p. 468). Referring to his work "*As a rule, a work presenting novel ideas will not elicit response if it lacks the support which comes from being written by a well-known author. We ought, therefore, to be surprise at response it met with rather than at the fact that it did not meet with more*" (p.469). Schumpeter said that he marvelled at the fact that Rae's book had been noticed by J. S. Mill and had often quoted in his famous book. In relation to this matter he stated: "*J.S. Mill was invariably fair and generous…the most influential textbook of economics, was insufficient to introduce Rae to the profession or to rouse any curiosity concerning the rest of the book! Or, alternatively, if this impression is wrong and any considerable number of Mill's readers did take it up, there was not one among them to realize its true importance*" (p.469). Brewer (1998) said that Schumpeter had been influenced by Rae but the difference between them concerning the study of development is what Schumpeter called vision rather than analysis.

Towards the end of the 1900s, some scholars published a series of articles on Rae highlighting above all the relationship between economic growth and technological change within his philosophy. Brewer (1991; 1998) analysed in great depth the differences between Rae's and Smith's thoughts concerning the sources of economic growth. Rae accused Smith of ascribing economic growth exclusively to the accumulation of capital that in turn depended on individual saving decisions. Rae was, according to

Brewer, the first economist to view technological change as the main cause of economic growth. Furthermore, both Smith and Rae believed that savings must be invested. The first, however, was a supporter of laissez-faire and thought that State intervention reduced savings and as a consequence the economic growth; Smith considered saving as an exogenous variable. In Rae's doctrine savings, population and invention were endogenous variables; moreover, growth was a function of innovation:

> It is invention, which showing how profitable returns can be got for the capital, and subsistence procured from the population that may most fifty be esteemed the cause of both, (Rae 1834: 31).

In Rae's opinion invention needed to be supported in order to promote saving; its causes were independent from individual saving decisions, causes that were open to the legislator's influence, while individual saving decisions were not. Another distinction between Smith and Rae is the cause relation between division of labour and invention. The first maintained that the division of labour led to the creation of new machinery and therefore of inventions, while the latter (Rae) claimed that inventions led to the division of labour.

In his article, Ahmad (1996) gave a more specific description of Brewer's interpretation concerning Smith and Rae; here is what he stated:

> Brewer's position that for Smith the division of the labor is implied by accumulation is not fully supported by evidence from "The Wealth of Nations". This also means that invention is not implied by accumulation either, since for Smith invention results directly from the division of labor. Hence accumulation and the division of labor (leading to invention) remain two separate elements in the process of growth… Let us now turn to Brewer's generalization concerning Rae-That for him invention is the sole independent cause of wealth and growth of income, and all other factors, including accumulation, are simply its consequence. The idea is encapsulated in Brewer's already cited praise of "Rae's conception of growth as wholly driven by invention (Brewer, 1991: 11). However, a quotation Brewer himself cites from Rae would seem to negate this position (Rae 1834: 264). Thus, the results of the two principles can be added indicating a parity of significance between the accumulative principle and the principle of invention, rather than the dominance of one over the other and certainly not one as a by-product of the other. In numerous other places, Rae attributes the difference in the economic growth of difference societies to

> differences in their accumulative principle (Ahmad, 1996: 444-445).

Anyhow, Ahmad agreed with Brewer on Rae's causality that inventions imply the division of labour. Finally, Wakatabe (1998) stated that, in his book, Rae had attempted to piece together a theory of growth that is knowledge-based, i.e. an endogenous model of growth, and drew an accurate analysis and interpretation of this model. A thorough treatment of Rae's thought was presented in Aberdeen on the occasion of a conference for the bicentenary of his birth (Rae, 1996; 27th-29th March). Input from various scholars who participated in the conference was collected in the book *The economics of John Rae* (Hamouda *et al.,* 1998). Moreover, The Canadian Economic Association (CEA), since 1994, offers the Rae Prize every two years. The CEA argues that: the prize has been named after John Rae born in Scotland in 1776, who did most of his work in Canada and was a genuine precursor of the endogenous growth theory.

The research carried out in this paper shall focus on Chapter X of Rae's Second Book, entitled *Of the causes of the progress of invention, and of the effects arising from it*, because, in my opinion, it includes some important concepts regarding the economics of innovation of which Rae was a forerunner, in addition to an early definition of that branch of economics which has today taken on a fundamental role in explaining the development laws of modern economic systems.

## The roots of the economics of innovation among philosophy, history of technology and economics

> Invention is the most important of the secondary agents, to the influence of which man is subject (Rae, 1834: 208).

Considering the title of Rae's chapter that is being analysed here, he referred to the progress of inventions, from which it can immediately be understood that the difference between invention and innovation was not wholly clear to him, a distinction that was later explained by Schumpeter, as pointed out above. That being stated, the aim of this section is to underline the significance of Rae's work because his writings anticipated several important concepts that were later developed within the economics of innovation. Rae's doctrine was based on three crucial factors (Brewer, 1998): 1) invention had causes that were different (and antecedent) from the current level of saving; 2) laissez-faire generated an invention equilibrium level that was second best; 3) State intervention could and should have brought the invention equilibrium to an first best situation.

The first concept that will be pondered upon is that of incremental innovation, which according to the more recent literature is a set of elementary improvements of the product and of the production process. In relation to this, Rae drew some remarks that anticipated such a concept, by showing how improvements were stimulated by need:

> Tracing any invention upwards to its first beginning, we shall discover, that these have been exceedingly rude and imperfect, proceeding from the simplest, and what would seem to us, the most obvious observations; and that it has advanced towards perfection, by having been led to change the materials with which it originally operated, and passing from one to another, has at each step of its progress discovered new qualities and acquired new powers (Rae, 1834: 224).

Another concept Rae developed regards the learning process, which is important for almost all scientific discoveries and has become one of the cornerstones of the evolutionary theory of economic change (Nelson & Winter, 1982; Dosi, 1988; Malerba, 1992),

> Abstract and scientific truth can only be discovered, by deep and absorbing meditation; imperfectly at. first discerned, through the medium of its dull capacities, the intellect slowly, and cautiously, not without much of doubt, and many unsuccessful essays, succeeds in lifting the veil that hides it (Rae, 1834: 213-214).

As stated above, in fact, in his book Rae meant to make up for the lacks in Smith's work by singling out the true causes that generated the wealth of nations and in doing so he designated the following elements as the causes of the progress of inventions:

a. firstly, he talked about the intelligence of men of genius; while Schumpeter maintained that the engine that pushed the system towards development was the innovating entrepreneur, Rae believed that the genius was the one who put to work an energy that without him would have remained at a standstill; moreover, Rae distinguished men of genius from common men who were characterised by an natural inclination towards imitation. In addition to this, Rae also distinguished inventors from people who simply passed knowledge on:

> It is thus that genius manifest the potency of the principle that inspires it, and that the simplest lays of the simplest bard, may have a power passing far, that of the triumphs of the statesman, or the warrior. The one wakens energy, otherwise dead, into action, the other merely directs that action (Rae, 1834: 211). It is necessary to premise, that for the present purpose, two classes occasionally confounded

> together, must be kept apart. Real inventers, the men whom we have alone to consider, differ from mere transmitters of things already known. The latter are an acknowledged, and very useful class, in all societies, but, they neither encounter similar difficulties, nor produce similar effects to the former (Rae, 1834: 213). The inquirer into principles, again, takes a wider range, it is not tile morality or religion of Italy, of France, of Britain, of North America, after which he seeks, but religion and morality in general (Rae, 1834: 218).

b. the second cause of the progress of invention was the scarceness of certain materials

> Some metals are found in quantity pure, the ores of some are easily reduced, of others with great difficulty. Of all the substances he attempts to classify, none, from their number and variety, give greater trouble to the mineralogist. The discovery of the qualities of such portions of these metals as were found pure, would soon make them be considered as the most useful of substances, and occasion their being sought after with avidity. The supply of them in this state being exhausted, or they who had employed them moving into regions where they could no longer be found, recourse would gradually be bad. to the more pure and more easily reduced ores, and from thence to metals, and ores wrought with greater difficulty. Thus we find that gold, silver, and copper, the metals that most frequently occur native, were those first in use; iron came last, and was probably then esteemed the most precious. Weapons of gold and silver were edged with it, in the same manner as were wooden implements, such as the old English spade, in more recent days. But for the gentleness of the ascent, it is altogether likely, that the art would never have attained the eminence it has gained. Had the earth, for instance, possessed no metallic stores but the more abundant ores of iron, by far the most useful in the present days, it seems not unlikely, that no metal would ever have been wrought (Rae, 1834: 226).

c. the third cause was the fusion of principles originating from within different fields or principles that were already known but were applied to new fields and, as is manifest, generated synergies thanks to phenomena that are today called cross-fertilization phenomena. These made it possible for inventions and innovations to develop following a geometrical rather than an arithmetical progression. Rae quoted watermills as an example:

> When arts are brought together, they borrow from each other. Men perceive that some materials, or instruments, or processes, employed in the one, could they be transferred to the other, would be the cause of its yielding larger returns.

> They are encouraged, therefore, to attempt the change, and experience shows, that such attempts perseveringly pursued, are generally successful (Rae, 1834: 237).
> Thus, from the union of the productions of the inventive faculty exercised on at least three arts, came the rude model of the present water-mill. Its progress was at first slow.
> It was owing to an invention, like so many others, the result of necessity and genius united, that the use of water-mills became more general.
> Important as these engines were in themselves, from their immediate utility, they were more so in their effects. Men's minds were directed to the advantage of what is termed machinery, instruments that is giving new velocity and direction to motion, and to the power of inanimate agents, generative of motion, of both which the mill afforded the first eminent instance.
> The productions of the union of arts also propagating others, like all generators, their increase goes on, to borrow a phrase of common use in inquiries connected with these, when there are no retarding checks, not in a simple arithmetical, but in a geometrical progression (Rae, 1834: 243-245).

In Rae's opinion, this effect as well as technological progress was made easier where there were men who belonged to different cultures and where there were consistent trade and financial dealings:

> I take it, that it is chiefly from this circumstance, that the seats of commerce have been. so generally the points, from whence improvements in the arts have emanated.
> Thus, also, countries where various different races, or nations, have mingled together, are to be noted, as coming eminently forward in the career of industry. Great Britain is a remarkable instance of this; so are the United States of America. When individuals meet from different countries, they reciprocally communicate and receive the arts of each, adopt such as are suited to their new circumstances, and probably improve several. Servile imitation can there have no place, for there is no common standard to imitate. Countries again, where only one art is practised, and where the population is composed of one unmingled race, are generally servilely imitative. Such are some purely agricultural countries.
> In modern Europe, too, the strength of the effective desire of accumulation, seems to have been always greater, than in any other part of the old world.
> It is worth while to remark, that there is a considerable analogy in this particular, between the different conditions of society in that continent and Asia then, and what exists

> between them now, in Europe and North America. The general wages of labor seem always to have been higher in Europe, than in Asia, in the same way as the wages of labor in North America, are now higher than in Europe. The same process, too, that carried the arts to Europe, seems now aiding their passage across the Atlantic. As flame often sets against the wind for that it is fed by it, so invention seems to hold its course against opposing obstacles,. for these obstacles excite its powers and minister materials to their action (Rae, 1834: 237-239).

Furthermore, according to Rae (1834), a multiethnic environment created large-scale habits and originated what today is known as the global village;

d. social changes were the fourth cause. In Rae's opinion, social events able to shake the motionlessness of systems stimulated the inventive and creative faculties of men; therefore, by means of revolutions (social and/or cultural) systems moved from involutive states to evolutive states making it possible for inventions and innovations to find a push towards development:

> But, though there are two of the circumstances giving strength to the principle of accumulation, on which the progress of the inventive faculty is equally dependent, there are yet a set of causes, the effects of which, while they paralyze the exertions of the one, rouse the other to activity. Whatever disturbs, or threatens to disturb, the established order of things, by exposing the property of the. members of the society to danger, and diminishing the certainty of its future possession, diminishes also the desire to accumulate it. Intestine commotions, persecutions, wars, internal oppression, or outward violence, either, therefore, altogether destroy, or, at least, very much impair the strength of the effective desire of accumulation. On the contrary, they excite the inventive faculty to activity. The excessive propensity to imitation, which is natural to man, seems the only means by which we can account for this diversity of effects. Men are so much given to learning, that they do not readily become discoverers. They have received so much, that they do not easily perceive the need of making additions to it, or readily turn the vigor of their thoughts in that direction. "They seem neither to know well their possessions, nor their powers; but to believe the former to be greater, the latter less, than they really are." Whatever, therefore, breaks the wonted order of events, and exposes the necessity, or the possibility, of connecting them by some other means, strongly stimulates invention. The slumbering faculties rouse themselves to meet the unexpected exigence, and the possibility of giving a new, and more perfect order t elements not yet fixed, animates to

a boldness of enterprise, which were rashness, had they assumed their determined places. Hence, as has often been remarked, periods of great changes in kingdoms or governments, are the seasons when genius breaks forth in brightest lustre. The beneficial effects of what are termed revolutions, are, perhaps, chiefly to be traced, to their thus wakening the torpid powers; the troubling of the waters they bring about, undoes the palsy of the mind.… (Rae, 1834: 222-223). War itself, so great an evil to the individuals within the scope of its ravages, is evidently the only manner by which, in certain states of society, an amelioration can be induced.

The aim of science may be said to be, to ascertain the manner in which things actually exist. (Rae, 1834: 255-256).

e. the fifth cause was the stimulus caused by need

Necessity thus taught its inhabitants the general use of coal, in which, happily, its territory abounds. But what of this material lay close to the surface, and the fields immediately beneath, having been wrought out, the miner was urged on by the increasing wants of his countrymen, and the abundant materials before him, to penetrate still deeper, and the labors of generations formed large excavations, in regions, far beneath the surface (Rae, 1834: 245).

f. finally, science was also a factor

In the ancient world, science, as founded on a generalization of the experiences of art, was little prosecuted. It is only in modem times, that the science of experience has come to form an element of importance, in the general advance of invention.

It is clearly on the antecedent progress of art, that the foundation of the hopes of Bacon, for the future progress of science, rested. His philosophy may be fitly described, as a plan to reduce to method the chance processes that had been going on before, by which men, as we have seen, happening on one discovery after another, grope their way, as he expresses it, slowly, and in the dark, to fresh knowledge and power. The progress of the philosophy to which he has given his name, as well as that of the science of mathematics, have unquestionably discovered to us many general truths, and theorems of art, and form therefore a new element influencing its progress. The great moving powers will, however, still, I apprehend, be found to proceed from the principles, the action of which we are now to attempt farther to trace through particular instances (Rae, 1834: 240).

It is indeed true that the philosophy, in the introduction of which he bore so eminent a part, has, in these latter ages,

> been a very effective promoter of the dominion of man, and, mixing with art, has much purified and dignified its spirit, and greatly increased its powers, turning invention in this department from particulars to generals, and converting art into science. This has more especially happened in the chemical sciences, and those connected with them, a sphere to which, I may be allowed to observe, his system seems particularly applicable. There, science begins to lead and direct art; in other departments she rather follows and assists it (Rae, 1834: 254).

Moreover, Rae underlined how the inventive faculty increased industry's rewards, thus anticipating the strategic importance of innovation for the growth of firms and sectors:

> The attempt, then, would probably never be made, but for the promptings of necessity. Its success has, two advantages. The subjection of the obstacles carries the inventive faculty a step farther forward; the larger returns made, owing to the circumstances in which the new material is superior, increase the rewards of industry. As the success of the attempt would advance the skill and the power of those who made it, so its failure would abandon them to famine (Rae, 1834: 225).

Rae tried to explain his theories by means of practical examples such as the steam engine, by pointing out the following main causes that made its invention and innovation easier (Rae, 1834: 246-247): 1) the difficulty to perform complex tasks; 2) the progresses in basic researches on latent heat; 3) the abundance of raw materials in England; 4) the presence of risk capital supplied by the entrepreneurial class, which is today known as venture capital.

Once inventions, and I would add innovations too, were originated, Rae indicated the causes that held them back:

1. the natural human inclination towards imitation;
2. the oppositions to already consolidated habits; this concept has been mentioned again in later works of economic literature on innovation, especially by Arthur (1989) who showed the so-called lock-in effects that inferior technologies can have in relation to superior ones due to the abilities acquired by the adopters in using them;
3. the commercial aspects that drive exclusively towards researches that have an immediate application. In relation to this, Rae quoted a significant passage by Bacon (1629) which said

> There, the observations of Lord Bacon apply nearly as forcibly as ever. "It is enough to restrain the increase of science, that energy and industry so bestowed, want recompense. The ability to cultivate science, and to reward

it, lies not in the same hands. Science is advanced by men of great genius alone, while it can only be rewarded by the crowd, or by men high in fortune or authority, who have very rarely themselves any pretensions to it. Besides, success in these pursuits is not only unattended by reward or favor, but is destitute of popular praise. They are, for the most part, above the conceptions of the commonalty, and are easily overthrown, and swept away, by the wind of popular opinion (Rae, 1834: 216-217).

In analysing the creation of knowledge Rae used a philosophical framework according to which the empirical data was the starting point from which the theory was derived, a questioning approach reminiscent of Locke:

> The progress of the knowledge of the natures and qualities of particular substances, gradually introduced a knowledge of the properties and natures of substances in general. Men first see in the concrete, afterwards in the abstract. Thus, the discovery of the several mechanical powers, and the knowledge acquired of the nature of each, led in time to the general principles of mechanics. A knowledge of the mathematical properties of substances, as in land-measuring, and in the regular figures of architecture, led to a perception of the general properties of figure, or of space as an affection of matter, and, at last, to the doctrine of pure space and motion (Rae, 1834: 239-240).

By continuing the analysis of his book, it is relevant to mention Rae's remark that the spatial diffusion of innovation from one country to the other where there are different cultures, climates and socio-economic environments, stimulates the inventive faculty and leads to further improvements. Concerning steam engines, he stated:

> The diversity of climates, territories, productions, other circumstances of different regions and nations, has helped it, as them, forward, and been to it as it were steps, by which, it has gained the rank it holds in the modes of human industry. Thus the peculiar circumstances of the North American continent, may, with propriety, be said to have been the exciting cause producing steam navigation, one of the most important of these steps. That country is full of great lakes and rivers, affording the easiest, and often the only means for the transport of the larger quantities of agricultural produce, that its interior sections yield.
>
> Such inland navigation is always exceedingly tedious; there were therefore peculiar reasons for the devise of some new agent to facilitate it. An agent like steam too, might evidently be employed with more safetyand chance of

> success, in calm inland waters, than in the great ocean. If we consider, in addition to this, the greater play which, from circumstances already enumerated, the inventive faculty enjoys in that continent, we shall see that it was there, so to say, that this improvement ought to have taken place. The point, too, in North America, where it did first actually take place, is also, as it were, particularly marked out for it. The transport between New York and Albany, by sailing, vessels on the Hudson river, was both very expensive, and pecularity tedious. Steam has there changed a voyage of days, or weeks, into one of less than sixteen hours.
> The circumstances leading on to the invention of steam land carriage, may also be noted as exemplative of this view of the subject. There were first simply railroads, to facilitate heavy drafts for short distances, from coal mines; then there was a more general use of them in all heavy drafts; finally, there was the general application of steam, as the power to effect transport of all sorts, and with all velocities, along, the smooth surface they afforded. All that was wanted for the last step was, that the mechanism should be rendered less heavy and cumbersome, and, it may be remarked, so great confidence bad been generated of the power of the inventive faculty, that the undertaking was commenced with full assurance that it would accomplish the desired improvement, although the manner how was not known. The result showed that the confidence was not misplaced…
> Thus, such are the steps by which invention advances, that it would seem, had there been no country like Great Britain, the steam engine might not yet have been produced; had there been none like North America, steam navigation might not yet have been practised; and again, had not Great Britain existed, metal railways and steam. carriage might have been still only in the category of possibilities (Rae, 1834: 248-249).

Incremental improvements due to technology occurred, in Rae's opinion, not only in relation to products but also in relation to services. On this matter he talked of an art that was intimately connected to the increase of wealth, that of bank trade. It had originated in the cities of Venice, Florence and Genoa, where there were frequent exchanges of substantial sums. In those societies, however, banking operations were limited to simple transfers of money. When the above-mentioned operations moved to areas where the amount of the exchange was small, like in Scotland, the inventive faculty contrived a way of facilitating, stimulating and increasing exchanges. Rae quoted a significant passage taken from

Smith's *The wealth of nations* that explained such a concept very clearly

> The following extract from the Wealth of Nations will render this apparent.
> "The commerce of Scotland, which at present is not very great, was still more inconsiderable when the two first banking companies were established; and those companies would have had but little trade, had they confined their business to the discounting of bills of exchange. They invented, therefore, another method of issuing their promissory notes; by granting what they called cash accounts, that is, by giving credit to the extent of a certain sum, (two or three thousand for example), to any individual who could procure two persons of undoubted credit and good landed estate to become surety for him, that whatever money should be advanced to him, within the sum for which the credit had been given, should be repaid upon demand, together with the legal interest. Credits of this kind are, I believe, commonly granted by banks and bankers in all different parts of the world. But the easy terms upon which the Scotch banking companies accept of repayment are, so far as I know, peculiar to them, and have perhaps been the principal cause, both of the great trade of those companies, and of benefit which the country has received from it" (Rae, 1834: 250-251).

Rae remarked also on some important implications related to the effects of the diffusion of inventions and, as a consequence, of innovations in terms of well-being (Rae, 1834: 260-61) that are summarised below:

- the increase of income both on an individual and on a social level;
- society can engage in doing new things;
- taxes can be paid on income and not on capital;
- the use of new materials.

In fact, he stated

> In this manner all improvements, by moving, the whole stock of instruments belonging to any society, to more productive orders, increase proportionably, its absolute capital and stock. Should a naturalist, in examining the nature of the surface, on the farm of an individual in a small agricultural society, make the discovery, that beneath it there was a quantity of plaster of Paris; and should the farmer, in consequence of his recommendation, sprinkling a little of this reduced to powder on some of his fields, find that it caused them to yield double returns, his farm or the lease he held of it, might, in his eyes be doubly valuable, and he might demand in exchange, and perhaps receive two

other farms of equal size in its place. Were it, however, found, that a stratum of this substance extended over the whole range of country possessed by the society, and was equally efficacious when applied to any portion of the surface, his farm would not be more valuable than other farms. The supply, however, for future wants, possessed by the whole society, would be largely increased, and the strength of their effective desire of accumulation remaining undiminished, their absolute capital would be proportionably augmented. But, as the whole stock of instruments remained the same, with the exception of the difference made, by the surface having been sprinkled with a quantity of this mineral powder, their amount, as measured by one another, would be the same as before. Some instruments might possibly exchange for a greater amount of instruments of another sort, than formerly, but this change could no more be considered an increase in the total value, than the fact of the latter instrument exchanging for a less amount, could be considered an indication of a diminution of the total exchangable value of the stock of the society. The relative capital and stock would thus remain unchanged. But, though this relative or exchangable value of the society's stock might remain unchanged, its absolute capital and stock would be increased (Rae, 1834: 259-260).

The reality of such increase is marked, in all similar cases, by at least three circumstances.

1. The members of the society possess, in general, a more abundant provision for future wants, the revenue of the whole society, and of each individual composing it, is increased.

2. The whole society, as a separate community, becomes more powerful, in relation to other communities.

3. As it is the effect of improvement, to carry instruments into orders of quicker return than the accumulative principle of the society demands, a greater range of materials is brought within reach of that principle, and it consequently forms an additional amount of instruments…

It can support the burdens of war, and the expense of all negotiations and national contracts with foreign powers, with greater case. It can also, without, inconvenience, execute a greater number of useful works and undertakings. The imposts which the state levies for such purposes, in a society where the stock of instruments is wrought up to an order correspondent to the average, effective desire of accumulation of its members, must almost always occasion some diminution of that stock. The returns coming in from their industry, being only sufficient to reconstruct the

> instruments as they are severally exhausted, an additional drain made upon their funds must, in most cases, prevent the reconstruction of many of them, and consequently occasion a disappearance, to that amount, of a portion of the general stock. But, when instruments are of more productive orders than the effective desire of accumulation of the society demands, the abstraction of a part of their returns by the state, to supply its exigencies, only carries them nearer, or brings them altogether to an order corresponding to the strength of that desire, and, therefore, interferes not with their reconstruction. Taxation is paid out of revenue, not out of capital. (Rae, 1834: 260-61).

Finally Rae also declared that the increase of the wealth of nations can be the effect of two principles:

1.the accumulative principle that generates the accumulation of capital;

2.the inventive principle that generates an increase of capital.

Essentially, the first principle generates a quantity of stock (accumulation of capital) that is increased by invention (volume of flow).

> It thus appears, that it is through the operation of two principles, -the accumulative, and inventive, that additions are made to the stocks of communities. It would contribute something to accuracy of phraseology, and therefore to distinctness of conception, to distinguish their modes of action by the following terms:
>
> 1. Accumulation of stock or capital, is the addition made to these, through the operation of the accumulative principle.
> 2. Augmentation of stock or capital, is the addition made to them, through the operation of the principle of invention.
> 3. Increase of stock or capital, is the addition made to them, by the conjoined operation of both principles.
>
> Accumulation of stock diminishes profits; augmentation of stock increases profits; increase of stock neither increases nor diminishes profits. (Rae, 1834: 264).

One of Rae's most significant contributions was, in my opinion, the establishment of an early definition concept concerning that branch of economics that was later called economics of innovation and that I have tried to perfect in the light of following contributions within economic literature. Rae said:

> It is the intention of the inventive faculty, when it applies itself to the arts ministering to the necessaries, conveniences, or superfluities of life, -to the wants of our nature that the subject we treat of considers, to increase the supplies- which it is the aim of each to procure. If when it gains the ends it purposes, it really produces this increase, in doing so, it must render the labor of the members of the

> society in which it operates more effective, and enable them from the same outlay to produce greater returns, or from less outlay to produce the same returns (Rae, 1834: 258-259).

Inventions can be distinguished as autonomous or induced inventions. The first type represents a long-term contribution of a fortuitous genius who through the application of intuitive ideas to existing technology (art according to Rae's terminology), increases the set of technical knowledge. This is the kind of invention discussed in Rae's book. Induced invention, on the other hand, is the deliberate employment of time, resources and efforts in order to promote new technical knowledge. This type of invention is born in Research and Development (R&D) laboratories. In these, the basic models that explain the origin of invention and of innovation are two: the technology push model characterised by a systematic research and development activity and the demand-pull model deriving from marketing activities (Dodgson & Rothwell, 1994). In any case, there is not just one factor, which the innovative activities of the industry stems from; instead, these emerge from a complex interaction of a multitude of factors and, very often, luck plays an important role. A pure accident led Luigi Galvani in the 18th century to make the legs of a frog contract when he linked a set of different materials. Even though Galvani had not wholly understood the nature of the phenomenon, it raised a widespread interest within the scientific community that led to a series of following systematic experiments and to the discovery of the electric battery. Other examples are the laws on polarisation of reflected light, the production of penicillin, the discovery of radioactivity and so on. This highlights an outstanding feature of innovation activities, i.e. an element of unpredictability. Although the role of systematic experimentation in the invention process is a generally acknowledged characteristic, little attention has been given to the random nature of discoveries. Furthermore, the origin of new techniques largely depends on the passing of time and on the accumulation of relevant technical abilities. In fact, lessons learnt from mistakes made in the past are an important element in a successful innovation process. According to Sahal (1981), the creation of an invention is not wholly random but it is guided by underlying logic deriving from what has been learnt from past experiences. Some probabilistic schemes based on negative distributions of the binomial type have created models regarding the origins of innovations by taking into account the cumulative learning process. Regarding Schumpeter's distinction between invention and innovation, some authors (Ruttan, 1971; Jossa, 1965) consider it of scarce utility for economic analysis. In fact, in certain practical cases it is difficult to single out the point where invention finishes and innovation begins (Cozzi, 1979). From what has been said it is possible to determine that it is not easy to define the field of analysis of invention and innovation, which can concern both the subjects and the objects of innovation (Archibugi, 1988).

In any case, drawing from Rae's quote the following can be stated.

The Economics of Technological Innovation studies the inventive and creative faculty, born in a random and/or systematic manner on the basis of a cumulative learning process, applied to industrial usages (object) in order to satisfy needs, to increase individual and social well-being, to make man's labour more effective and efficient and to generate economic growth.

Furthermore, the economics of innovation analyses the sources of knowledge and those who make use of it (subjects) as well as their interdependence on economic systems (sectors) and political systems (States and nations). It finally studies the impact of innovation on the structure, strategies and performance of firms, its spatial-temporal diffusion and its related impact on the geo-economic environment.

In other words, the economics of innovation is that branch of economics that studies innovative products, processes and organisations in order to satisfy the necessities and desires of mankind (needs). Their purpose is to increase the quantity that each individual is inclined to acquire and enables mankind to obtain more products at the same cost or the same amount of products at a lower cost in order to increase individual and social well-being.

Moreover, Rae stated that:

> An improvement in the construction of a plough, enables the individuals employing that instrument to plough a greater quantity of land with the same cattle and labor, or an equal quantity of land with fewer cattle and less labor. The use of water as a power diminishes very greatly the labor necessary to perform the operations in which it is employed, and, therefore, from a less outlay, produces equal returns (Rae, 1834: 259).
>
> It is here also to be observed that, although any particular improvement, immediately, and at first, affects only the instruments improved, it very shortly diffuses itself over the whole range of instruments owned by the society. The successful efforts of the inventive faculty are not a gift to any particular artists, but to the whole community, and their benefits divided amongst its members. If an improvement,

> for instance, in the art of baking bread were effected, by which, with half the labor and fuel equally good bread could be produced, it would not benefit the bakers exclusively, but would be felt equally over the whole society. The bakers would have a small additional profit, the whole society would have bread for the product of some what less labor, and all who consumed bread, that is, every member of the society, would from the same outlay have somewhat larger returns. The whole series of instruments owned by the society would be somewhat more productive, would be carried to an order of quicker return (Rae 1834: 259).
>
> The various agricultural improvements with which invention enriched that art in Britain towards the conclusion of the last, and commencement of the present century, occasioned a great amount of materials to be wrought up, which before lay dormant. The construction of the plough in Scotland, and generally over the island, was so improved that two horses did the work of six oxen. The diminution of outlay thus produced, giving the farmer, from a smallercapital, an equal return; he was encouraged and enabled to applyhimself to materials, which he would otherwise have left, ashis forefathers had done, untouched. He carried off stones from hisfields, built fences, dug, ditches, formed drains, and constructed roads.
>
> Nor was this all; the stimulus reacted also on the inhabitants of the towns, and their industry was augmented by the increased returns yielded by the country, and by the new demands made by it. Improvements, too, in the branches of industry in which they were themselves engaged, of at least equal extent, carried them forward in a like career (Rae, 1834: 261-262).

## Concluding observations

John Rae has recently been rediscovered as a genuine precursor of the endogenous growth theory. I think, he needs to be rediscovered a second time for his contribution to the understanding of the economic role played by the innovation and technology change within the economic system. Moreover, his penetrating and original insights into the invention put forward the basis of the economics of innovation.

The first economist who discovered the significance of Rae's work was John Stuart Mill (1848) who in his famous book *Principles of Political Economy* repeatedly praised Rae's analyses concerning the causes that bring about the accumulation of capital. Mill said *in no other book known to me is so much light thrown, both from principle and history, on the causes which determine the* *accumulation of capital* (Bladen & Robson, 1965: 162). Mill put Rae's notions into the framework of the orthodox paradigm and by means of his concept of stationary state, he eliminated any possibility of considering the accumulation principle and the invention principle as antagonistic of each other. Although Mill's book had been very much appreciated by American protectionists, little acknowledgment was given to Rae; however, the greatest among protectionist scholars borrowed many ideas from Rae himself. In Italy, Ferrara (1856), following in Mill's footsteps, remarked that Rae's work was full of new concepts, above all concerning the formation of capital and the elaboration of a precise theory of value formulated according to the most modern investigation techniques. After such positive remarks on Rae, the scholar did not meet with very much success maybe also because of his ideas, which were too innovative for the period in which they were conceived.

The analysis of his work is, however, very stimulating and it leads to some obvious questions: why did Rae, disagreeing from Smith, explain the economic growth through the invention? Why did Rae establish a correct relation between invention (cause) and division of labour (effect)?

As Brewer (1991; 1998) suggested, Smith conceived his book when the industrial revolution was still in its embryonic phase. In fact, the steam engine was invented by Watt in 1775, the first steam vehicle with four wheels dates back to 1802, steam navigation to 1807 and the first steam locomotive to 1813. The main innovations relating to the invention of steam came therefore after Smith's book and before Rae's work. The latter travelled around the old and the new world and had the chance to observe the main applications of the steam engine, as proven by his descriptions of steam navigation and the steam locomotive (he also provides an account of the innovation of movable type printing invented by Gutenberg in 1455 already existing at Smith's times); his acute remarks as well as the power of his analysis led him to explain economic growth as driven by invention and to recognise the relevance of those phenomena that would later be called revolutions of the techno-economic paradigm (Freeman *et al.*, 1982). Anyway, during the historical period when Rae wrote his works the industrial revolution was going through a growing phase, differing from Smith's period, and this influenced the author of the *New Principles* (1834). The presence of industrial revolution's great innovative wave also influenced the writings of other scholars, like Marx (1890; 1975) who claimed that the capitalist system had reached in one hundred years a level of economic progress that previous generations had not been able to reach in one thousand years.

Smith must be granted the great merit of having been the first scholar to handle economic phenomena in a systematic manner, while Rae had the merit of having explained economic growth by means of new concepts regarding invention and of having broadened the field of economic science by establishing the primary elements of the economics of innovation branch. Referring to Grandstrand's statement (1994) that the origins of the economics of technology lie in Babbage's work written in 1832, two years before Rae's work, it must be remarked that Babbage's analysis had rather an engineer's edge to it, while Rae's writings had a strictly economic foundation and explained by means of philosophy, like Smith had done, the nature and causes of the wealth of nations and how innovation is important for economic growth. The difference between Rae and Babbage it is already the titles of their books. Babbage is the pioneer of the computer and the purpose in writing *On the economy of machinery* was to examine the mechanical principles, which regulate the application of machinery to arts (technology) and manufactures. Although Rosenberg (1971) stated that Babbage's book deserve to be regarded as possibly the earliest treatment of the economic determinant of inventive activity, he argues that the main contribution of Babbage's book is the considerable improvement upon the division of the labour and the first systematic analysis of the economies associated with increasing returns to scale. According to my opinion, the Babbage's contribution to the economic role played by invention and machinery in the course of industrial development is limited to the firms and using an approach of the engineering and information sciences.

Nowadays innovation has gained great significance and is the subject of numerous studies but, as previously stated, it is still difficult to define it and even more so to measure it. The explanation of this is that the origin and diffusion of innovation is a function of several variables and the study of its endogenous and exogenous dynamics cannot be carried out by means of only one topic, i.e. economics. This article has thoroughly analysed the work of an author who had an interdisciplinary learning (philosophy, mathematics, biology, physics, medicine, etc.), suited to the study of the technology, which allowed him to investigate invention and innovation in greater depth and to single out some fundamental concepts of the modern branch of economics that studies innovation. The defining concept here displayed drawn from Rae's analysis, of which a further refinement has here been attempted, is by no means meant to take on an exhaustive content but is intended as a first step towards correctly identifying the definition of economics of innovation.

Even though Rae had been praised by the English economist Mill, who believed Rae had clarified the causes of the accumulation of capital both from a theoretical and from a historical point of view, an attentive reader might raise the following question: why did Rae's correct economic analyses not assert themselves within the economics? The answer to such question is left to Mill (1848) who, concerning Rae's book, said

> This treatise is an example, such as not unfrequently presents itself, how much more depends on accident, than on the qualities of a book, in determining its reception. Had it appeared at a suitable time, and been favoured by circumstances, it would have had every requisite for great success. The author, a Scotchman settled in the United States, unites much knowledge, an original vein of thought, a considerable turn for philosophic generalities, and a manner of exposition and illustration calculated to make ideas tell not only for what they are worth, but for more than they are worth, and which sometimes, I think, has that effect in the writer's own mind. The principal fault of the book is the position of antagonism in which, with the controversial spirit apt to be found in those who have new thoughts on old subjects, he has placed himself towards Adam Smith. I call this a fault, (though I think many of the criticisms just, and some of them far-seeing,) because there is much less [MS, 48, 49, 52, 57 less of] real difference of [MS, 48, 49, 52 difference in] opinion than might be supposed from Dr. [MS, 48, 49, 52, 57, 62 Mr.] Rae's animadversions; and because what he has found vulnerable in his great predecessor is chiefly the "human too much" in his premises; the portion of them that is over and above what was either required or is actually used for [MS, 48, 49, 52 used in] the establishment of his conclusions. [MS conclusions.-Yet such are the conditions of celebrity, that if this author had attained it, the polemical character of his book would probably have been the hinge on which would have turned the accident of its exciting attention (Bladen & Robson, 1965: 162).

Today, however, it is easy to see that, despite the vicissitudes concerning the publishing of Rae's book and the little attention gained within the history of economic science, his work has recently raised considerable interest among scholars of economics, especially that of innovation, not only because of the originality of his exposition but also because he took into account the variable invention within his explanation of economic growth. The latter concept was later further analysed by Schumpeter himself and by Solow (1956). Moreover, the matter of economic growth explained on account of invention and technological progress and the extraordinary set of new concepts and relations included in Rae's book, premature for the historical period when the work was conceived, give it form and substance, still revealing, almost two centuries later, all their original innovative charge and proving up-to-date in explaining the evolution of modern economic systems.

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# 3. Evolution of the economics of science in the Twenty Century

## Introduction

Interest in the role that scientific research play in economics and the other social sciences has exploded in the last thirty years. This increased attention undoubtedly reflects the increased importance that scientific research is contributing to technological development, and as a consequence, employment and economic growth in Europe, North America and Asia (Romer, 1994; Porter, 1988)[1]. In response to this increased policy focus on science, scholars have generated a wave of studies and inquiry focusing on the economics of scientific research and innovation. While this new literature has its roots in classic articles written, in some cases, nearly half a century ago, it has the special characteristic of spanning a number of fields, not only within economics (such as labour economics, industrial organization, innovation and technological change, economic history, and even growth theory), but also other social sciences such as sociology, psychology and the management of technology. The field demands an understanding not just of economic and social forces but of

[1]Seestudies by Calabrese *et al.,* 2005; Cariola & Coccia, 2004; Cavallo *et al.,* 2014, 2014a, 2015; Coccia, 2001, 2003, 2004, 2005, 2005a, 2005b, 2005c, 2006, 2006a, 2007, 2008, 2008a, 2008b, 2009, 2009a, 2010, 2010a, 2010b, 2010c, 2010d, 2010e, 2011, 2012, 2012a, 2012b, 2012c, 2012d, 2013, 2013a, 2014, 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2015, 2015a, 2015b, 2015c, 2015d, 2016, 2016a, 2016b, 2016c, 2017, 2017a, 2017b, 2017c, 2017d, 2018, Coccia & Bozeman, 2016; Coccia & Finardi, 2012, 2013; Coccia & Wang, 2015, 2016; Coccia & Cadario, 2014; Coccia *et al.,* 2015, 2012, Coccia & Rolfo, 2000, 2002, 2009, 2012, 2007, 2010, 2010, 2013; Coccia & Wang, 2015, 2016; Rolfo & Coccia, 2005.

scientific developments as well. The wide range of scholarly disciplines involved in research on the economics of science and scientific research has made it difficult for scholars in any one field to grasp the research contributions and to offer courses, at either graduate or undergraduate level, on the economics of science and of scientific research. Although the field has much older roots, the contemporary basis for the subject solidified when the *Journal of Economic Literature* invited Paula Stephan to summarize what is known and not known about the economic analysis of science. Her response was *The Economics of Science*, which was published in the *Journal of Economic Literature* in 1996. Stephan (1996, p.1199) introduces the subject:

> Science commands the attention of economists for at least three reasons. First and most important, science is a source of growth. The lags between basic research and its economic consequences may be long, but the economic impact of science is indisputable. Second, scientific labor markets - and the human capital embodied in scientists - offer fertile ground for study. Third, a reward structure has evolved in science that goes a long way toward solving the appropriability problem associated with the production of a public good.

Despite the remarkable efforts made in the twentieth century, works attempting to deal with economics of research and science (Martin & Nightingale, 2000; Stephan & Audretsch, 2000; Garonna & Iammarino, 2000) do not yet have clear outlines, because it is easy to find in them subject matters concerning innovations that pertain to other sciences and/or disciplines. Furthermore, within the economic literature there is often a certain degree of confusion about the terms 'science' and 'research', commonly used as if they were synonyms, even though the two concepts are actually different. In view of such issues, the purpose of this article is to analyse, within the history of economic thought, the origins, nature and structure of the branch of economics defined as economics of scientific research. This is also useful to clarify the terms science, research, scientific research and their related taxonomies. In order to do so, section 2 analyses such topics, drawing attention to what can be considered the first definition of scientific research. After having highlighted the origins and nature of this important branch of economics, section 3 points out the main features of the discipline's structure, on the basis of numerous fields of research present in scientific journals. The last section of the paper focuses on some concluding remarks.

# Origins, nature and evolution of the economics of scientific research

The paper analyses the nature of scientific research, a type of research associated to science. Although there have been several contributions to this field of investigation in the last few years, the origins of this discipline can be traced back to classical economists. In fact, in the 1800s, when analysing economic phenomena and addressing subjects related to scientific research, several scholars referred to the terms science, philosophy, technology, invention, and so on. One of the first scientists who dealt with such topics was Francis Bacon[2], who believed that science had the power to improve the society's economy and standard of living. In his work *New Atlantis* (1629), he saw science, technology, politics, industry, and religion as deeply intertwined. Bacon is important because he was one of the first to suggest a link between organisation of science and economic progress. Bacon's work marked the beginning of a new way of thinking about the science. Since scientific research derives directly from science, in order to define the former, first of all it is best to clarify the concept of science.

The term science has been given different meanings by scholars. The great Scottish economist Rae (1834) maintained that:

> It is indeed true that the philosophy, in the introduction of which he bore so eminent a part, has, in these latter ages, been a very effective promoter of the dominion of man, and, mixing with art, has much purified and dignified its spirit, and greatly increased its powers, turning invention in this department from particulars to generals, and converting art into science. This has more especially happened in the chemical sciences, and those connected with them, a sphere to which, I may be allowed to observe, his system seems particularly applicable. There, science begins to lead and direct art; in other departments she rather follows and assists it… the aim of science may be said to be, to ascertain the manner in which things actually exist (Rae, 1834: 254).

Dampier (1953) provided one of the most prominent definitions of science and stated that:

> Ordered knowledge of natural phenomena and the rational study of the relations between the concepts in which those phenomena are expressed.

Russell (1952) gave a broader definition:

[2] Bacon isknownas the father of the English empiricistphylosophy, a traditionthatincludes Locke, Hume, J.S.Mill, Russel.

> Science, as its name implies, is primarily knowledge; by convention it is knowledge of a certain kind, namely, which seeks general laws connecting a number of particular facts. Gradually, however, the aspect of science as knowledge is being thrust into the background by the aspect of science as the power to manipulate nature.

According to Paul Freedman (1960) the definition of Bertrand Russell is the more satisfactory, while Dampier's definition relates only to scientific knowledge, and does not take into account either the application of such knowledge, or the power to apply it, towards control and change of man's environment. But though wider than Sir William Dampier's definition, Russell's definition is also open to a serious objection. It presents science as static, whereas it is intensely dynamic. The most important attribute of science is not knowledge, but its capacity for acquisition of knowledge. Knowledge which science contains is limited, frequently fragmentary and inaccurate, always liable to revision. The capacity of science to acquire knowledge is infinite. A different definition of science was provided by Crowther (1955), according to whom:

> Science is a system of behaviour by which man acquires mastery of his environment.

Alessandro Volta (1792)[3] put forward a concept of science that has its greatest and most rewarding moments in practical activity, but at the same time is somehow limited in the creation of a theoretical framework. For the Italian scientist, science is invention and it is characterised by the scientist's specific aptitude for the construction of devices and artefacts. Therefore, Volta interpreted the concept of science in an experimental sense. On the other hand, Thomas Kuhn (1969) claimed that:

> Science is a constellation of facts, theories, and methods… Hence scientific development is the fragmentary process through which these elements have been added, singularly or in groups, to the ever growing depository that constitutes technical and scientific knowledge.

Kuhn (1969) also talked about normal science, i.e. research that is firmly based on one or more results previously achieved by science.

Thus it may be seen that an adequate definition of science is difficult to frame. A perfect definition of science is, indeed, an impossibility, since an understanding of the nature of science, like science itself, changing with the passage of time, can only

[3]Alessandro Volta (1745-1827) Italianphysicist, known for hispioneering work in electricity, invented the ElectricBattery in 1800.

gradually approach to truth. An adequate definition of science must be wide enough to include all its aspects and, at the same time, rigid enough to exclude all that is no-scientific in reasoning, knowledge, experience and action. It must, while excluding activities, which are merely a haphazard accumulation of empirical knowledge and practice (like culinary and fashion art), include not only all the pure but also all the applied branches of science. An adequate definition of science, while excluding all practices of essentially magical nature, must include all genuine science even in its very early stages, however elementary and naïve. It must not only present science as dynamic, but take into account the fact that nature itself is not static, and that its laws are not immutable but change with time (Freedman, 1960). A definition that satisfies the above conditions is the following:

> Science is a form of human activity through pursuit of which mankind acquires an increasingly fuller and more accurate knowledge and understanding of nature, past, present and future, and an increasing capacity to adapt itself to and to change its environment and to modify its own characteristics (Freedman, 1960).

Brevity is essential to any definition. Consequently, no definition can give an exhaustive presentation of that which it defines. Its essential brevity is achieved at the cost of omission. After the definition of science, we focus on the concepts of research and scientific research.

"Research" in all fields of human activity means continued search for knowledge and understanding. *Scientific research differs from other kinds of research in that it is a continued search for scientific knowledge and understanding by scientific methods.* This dual determination of the scientific nature of a research - determination by objective and by method - is of fundamental importance. Not all knowledge and understanding is scientific and if anyone were foolish enough to search for the best spinet music or for understanding of a poem by scientific methods, he would not, in any sense, be engaged in scientific research. Knowledge and understanding of movements of heavenly bodies would, on theother hand, be scientific knowledge, but anyone searching for such knowledge by unscientific methods, for example by study of theological works, would, most certainly, not be engaged in scientific research. The meaning of the expression "scientific knowledge and understanding" follows naturally from the definition of science (Freedman, 1960).

Scientific research is not as old as science because scientific knowledge and understanding were impossible until the time when science reached a certain level of development that enabled to conceive the scientific method. John Rae (1834) said that:

> In the ancient world, science, as founded on a generalization of the experiences of art, was little prosecuted. It is only in modern times, that the science of experience has come to form an element of importance, in the general advance of invention.
>
> It is clearly on the antecedent progress of art, that the foundation of the hopes of Bacon, for the future progress of science, rested. His philosophy may be fitly described, as a plan to reduce to method the chance processes that had been going on before, by which men, as we have seen, happening on one discovery after another, grope their way, as he expresses it, slowly, and in the dark, to fresh knowledge and power. The progress of the philosophy to which he has given his name, as well as that of the science of mathematics, have unquestionably discovered to us many general truths, and theorems of art, and form therefore a new element influencing its progress. The great moving powers will, however, still, I apprehend, be found to proceed from the principles, the action of which we are now to attempt farther to trace through particular instances ... (p. 240).

The prodigious development of many sciences and technologies is pushed by the application of two scientific methods[4]:

- *inductive*, which starts from the experimental observation of phenomena and traces back the laws that regulate them by means of experiments, analogies, and hypotheses;
- *deductive*, which starts from the theory and the general ideas in order to predict new laws and therefore discover new phenomena.

The development of the experimental method was refined by Lazzaro Spallanzani[5] and consisted in varying incidental and environmental circumstances, to the point that it would be possible to almost completely eliminate all the interferences due to these factors. Scientific research, deriving from the application of these

[4] The origins of the scientificmethod date back to Aristotele (384 B.C.-322 B.C.), whowasone of the first to describe the deductiveprocess, while Bacon (1561-1626) was the first scientist to developaboveall the inductivereasoning, that Galileo (1564-1642) latercompleted by addinghismathematicformalisation.

[5] Lazzaro Spallanzani. (Italy, 1729-1799) is one of the great names in experimental physiology and the natural sciences. His investigations have exerted a lasting influence on the medical sciences. He made important contributions to the experimental study of bodily functions and animal reproduction. His investigations into the development of microscopic life in nutrient culture solutions paved the way for the research of Louis Pasteur.

two procedures, is divided into two important fields (Godin, 2001): basic research and applied research.

Basic research was first defined explicitly in taxonomy in 1934 by Julian S. Huxley and later appropriated by Vannevar Bush[6] (1945), while Cohen originates the concept of pure research in 1948. Philosophers distinguish between science or natural philosophy, that is motivated by the study of abstract notions, and the mixed "disciplines" or subjects, like mixed mathematics, that are concerned with concrete notions (Kline, 1995). Basic research came into regular use at the end of the nineteenth century and was usually accompanied with the contrasting concept of applied research. In the 1930s, the term “fundamental” occasionally began appearing in place of "pure". The first attempts at defining these terms systematically occurred in Britain in the 1930s, more precisely among those scientists interested in the social aspects of science. Bernal[7] used the terms "pure” and "fundamental" interchangeably. Huxley (1934), who later became UNESCO's first Director-General (1947-48), introduced and suggested the first formal taxonomy of research. The taxonomy had four categories: background, basic, ad hoc and development. For Huxley, ad hoc meant applied research, and development meant more or less what we still mean by it today. Frascati manual (OECD, 1968), instead, distinguishes among: **Basic research** is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts *[epistemological- general / reductionist]* without any particular application or use in view *[intentional].* **Pure basic research** is carried out for the advancement of knowledge without working for long-term economic or social benefits and with no positive efforts being made to apply the results to practical problems or to transfer the results to sectors responsible for its application *[intentional].* **Oriented-basic research** is carried out with the expectation that it

[6] Vannevar Bush director of the Office of ScientificResearch and Development whichwasalsoresponsible of the Manhattan Project.

[7]Bernalwas the first to perform a measurement of science in a Western country. In *The Social Function of Science* (1939), Bernalestimatedthe moneydevoted to science in the United Kingdom (UK) usingexistingsources of data: governmentbudgets, industrial data (from the Association of ScientificWorkers) and UniversityGrantsCommittee reports. He wasalso the first to suggest a type of measurementthatbecame the mainindicator of science and technology: Gross Expendituresn Research and Development (GERD) as a percentage of GrossDomestic Product (GDP). He compared the UK's performance with that of the UnitedStates and USSR (nowFederation of Russian States) and suggestedthat Britain should devote betweenonehalf and onepercent of itsnationalincome to research.

will produce a broad base of knowledge *[epistemological-general]* likely to form the background to the solution of recognized or expected current or future problems or possibilities *[intentional]* (Calvert, 2004).

As Joseph Needham (1959) says, there is no sharp distinction between "pure" and "applied" science - "There is really only science with long term promise of application and science with short term promise of application. True knowledge emerges from both kinds of science".

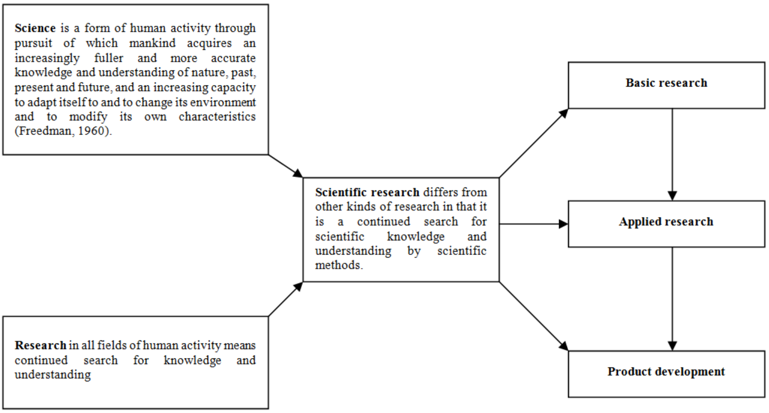


**Figure 1.** *Derivation of scientific research and its taxonomies*

One of the main outputs of the scientific research process is invention, which is often dealt with in books that talk about the economics of scientific research. Inventions can be divided into autonomous and induced. The first type is the long-term contribution of a casual genius who, by applying intuitive ideas to existing technologies, increases the set of technical knowledge. This is the type of invention investigated by Rae (1834) and widespread during the Renaissance that took place in European culture during the fifteenth and sixteenth centuries, when researches were commissioned to scientists (such as, Leonardo Da Vinci), who were financed by rich patrons. Induced invention, instead, is the deliberate use of time, resources, and efforts in order to promote new technical knowledge. This type of invention is created in Research and Development (R&D) laboratories and is the most common form of research in the modern age (Nelson, 1962).

Once scientific research and its typologies had been defined, the discipline dealing with its study, the "economics of research", started to make headway and to develop as an autonomous field of investigation in post-war times. Scientific and technical advances have always been important to military success, from the mass production of Springfield rifles in the American Civil war, to information, telecommunications and electronics in the Iraq war. Bernal (1939), writing between the two World Wars, was not optimistic about science. Barnal's work explicitly recognises the lack of direct link between social and scientific progress. During the Second World War, research began to be carried out mainly in corporate research laboratories, organisations having a staff of scientists with homogeneous and/or heterogeneous training and education. In fact, the scientists involved in the Manhattan project established one of the first research laboratories. The United States initiated this program under the Army Corps of Engineers in June 1942. Italian physicist Enrico Fermi managed the University of Chicago reactor, called Chicago Pile 1, and under the abandoned west stands of Stagg Field, the first controlled nuclear reaction occurred. The project had military purposes and led to the first atomic weapon. At the end of the war, alongside military research, laboratories began to conduct researches for civil purposes, above all focusing on the production of electric power. The project's conversion to different aims led to the creation of a series of laboratories in the United States, which are still renowned today for their advanced researches, for example the Sarnoff Corporation (http://www.sarnoff.com/) and the Los Alamos National Laboratory (http://www.lanl.gov). It was the success of the Manhattan Project that symbolised the power of big science projects involving governments, scientists, industrialists and universities. Moreover, it was on May 14, 1948, that project *RAND*-an outgrowth of world war II-separated from Douglas Aircraft Company of Santa Monica, California, and became independent, non-profit organization. Adopting its name from contraction of the term *research and development* the newly formed entity was dedicated to furthering and promoting scientific, educational, and charitable purpose for the public welfare and security of the United States. By early 1948, Project *RAND* had grown to 200 staff members with expertise in a wide range of fields including: mathematicians, engineers, economists, chemists, physics, aerodynamicists, and so on. For Bush, this success established a linear model from: *basic physics→large scale development→applications→military and civil innovations.*

The presence of laboratories made it possible to collect large series of data but it also brought policy makers face to face with the first issues regarding financing and effective management of organizations, whose main aim is the production of scientific research, which is beneficial for society and its wellbeing. Bush's view, that science should be publicly funded and left to itself in order to produce advances in technology, was influential on the post-war research policy in a period of economic growth. De Solla Price (1965) recognises the interaction between science and technology and uses the metaphor of two dancing partners who are independent but move together. These features together with specific historical circumstances related to the World War led to the birth and development of the economics of research. While the Stephan (1996) provides a contemporary view of science, we, go back to 1959 for the article *The Simple Economics of Basic Scientific Research*, Richard Nelson to trace some of the fundamental economic analyses concerning science that provide the basis of our modem understanding. However, the first scholar who really dug wholeheartedly into what, by any reasonable interpretation, can be called Economics of Scientific Research was Paul Freedman (1960) with is work *The principles of scientific research* published in London in 1949 by Pergamon Press Ltd. This remarkable work and author, and his treatment of economics of scientific research in particular, certainly deserve a scholarly study in its own right. Although today largely forgotten, the role of his 1949 book could from the point of views of economics of science and research to be considered to correspond to the role of Smith's "The wealth of nations" in general economics. After Freedman's book, around the 1950s, contributions to the economics of research became more and more numerous, so much so that today there are several journals that deal with its issues. Among them, some of the most prominent are: "Minerva: A review of science, learning, and policy" (established in 1962) by Springer; "Social Studies of Science: An international review of research in the social dimensions of science and technology" established in 1970 edited by Michael Lynch Editor; "Prometheus" edited by Routledge; and others that deal with more specific topics, as will be explained in the next sections.

Figure 2 places the beginning of the modern branch of the economics of scientific research around the 1940s, when the Second World War led to the institution of the first organised laboratories for the production of scientific research. In particular, the first edition of Freedman's book, dated 1949, can be considered to mark the date of birth of this discipline. Figure 2 also displays, in chronological order, the main contributions of economic literature that have helped the development of this field of investigation and that are described in the following section.

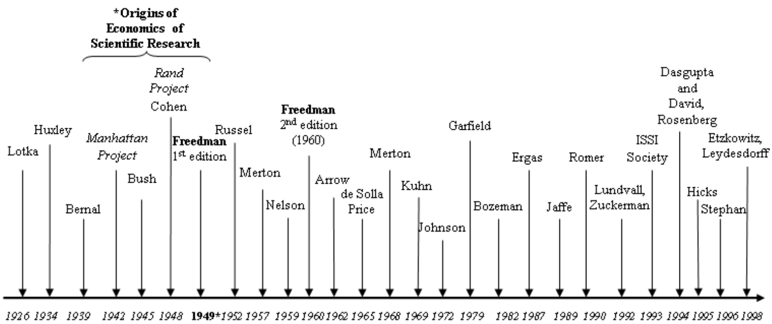


**Figure 2.** *Origins and evolution of the economics of scientific research and main contributions*

## Structure of the discipline

The content of the Book of Freedman (1960) is the following: part I presents the development of the process of research and its relationship with social change and available techniques; part II is the principles of the research process: types of problems, methods of attack, and essential disciplines (The mental approach to the research; the planning of research, the organization, the accuracy and economy of effort and the minimum number of essential observations). Part III is focused on the support available for research.

Since 1950s, several contributions (Stephan & Audretsch, 2000) have developed to the economics of the scientific research and the modern structure of the economics of scientific research could be based on the following central topics comprising the emerging fields: 1) The public nature of scientific research and financing; 2) Reward structure of scientific research; 3) Scientists and careers in scientific research; 4) Technology transfer and commercialization; 5) Knowledge spillovers; 6) Scientometrics and R&D Evaluation; 7) National and regional system of innovation and scientific knowledge; 8) Managerial and organisational behaviour of R&D laboratories; 9) Research policy; 10) Scientific research and economic growth.

❑ *The public nature of scientific research and financing.* The public nature of scientific knowledge appeared in the economics literature (Johnson, 1972), with the publication of Arrow (1962). He argues that within economic systems there are some goods that the markets either do not offer at all or do not offer in sufficient amounts. The public nature of science is based on the asymmetric appropriability of knowledge: subjects that bring about innovation generate social benefits that are not compensated by privately appropriable benefits. Within this neoclassical theoretical framework, public interventions in the scientific sector as well as the creation of remedies to the public nature of science are justified. The latter is done by means of patents, granting the exclusive use of knowledge for a limited period of time to those who have made a new discovery (Nordhaus, 1969). In view of the features mentioned above, an economic system based essentially on private agents, focused on maximising profits, would generate market failures, since private incentive does not make it possible to achieve a social optimum. In this sense, public financing bridges the gap between private investment and social optimum. Nelson (1959) justifies public aid to science with the inefficiency of the market of scientific knowledge. Callon (1994), by contrast, argues that the public nature of science is greatly overstated. He emphasises the tacit knowledge (Polanyi, 1966) can be more costly to learn than knowledge that is codified. Eisenberg (1987) states that publication of results is not equivalent to making the discovery a public good. Dasgupta & David (1994) argue that research findings become a public good only when they are codified in a manner that others can understand. They make an important distinction between knowledge, which is the product of research, and information, which is the codification of knowledge. They also argue the implications for appropriability and disclosure, that differentiate science from technology: 'If one joins the science club, one's discoveries and inventions must be completely disclosed, whereas in the technology club such findings must not be fully revealed to the rest of the membership' (Dasgupta & David, 1987, p. 528).

- *The reward structure of scientific research.* Merton (1957) argues that the goal of scientists is to establish priority of discovery by being the first to communicate an advance in knowledge, and that the rewards to priority are the recognition awarded by the scientific community for being the first. Zuckerman (1992) estimates that, in the early 1990s, around 3,000 scientific prizes were available in North America alone. This is the five times the number available two decades earlier. Stephan & Levin (1992) and Stephan & Everhart (1998) argue that scientists are interested in three types of rewards: 1) the puzzle, the satisfaction derived from solving a problem; 2) the ribbon, the recognition awarded priority and the prestige that accompanies priority; 3) the gold, the economic rewards that await the successful. Dasgupta & Maskin (1987) and, Dasgupta & David (1987) argue that there is no value added when the same discovery is made a second, third, or fourth time. To put sharply, the winning research unit is the sole contributor to social surplus. A defining characteristic of the type of winner-take-all contests analysed is inequality in the allocation of rewards. Scientific research has extreme inequality with regard to scientific productivity and awarding priority.

❑ *Scientists and careers in scientific research.* The first research on the frequency distribution of scientific productivity is by Lotka (1926). Levin & Stephan (1991), instead, analyse the productivity of scientists during their scientific life cycle, while other studies confirm that scientific productivity is asymmetrically distributed throughout the population of researchers (Allison & Stewart, 1974; David, 1994; Fox, 1983). In fact, a study by Ramsden (1994) about 18 Australian universities shows that, over a 5-year period, 14% of the total number of researchers produced 50% of the publications, while 40% of researchers produced 80% of publications. The explanation for the high productivity of some researchers derives from cumulative learning processes, among which the Matthew effect (Merton, 1968). This shows how researchers who accomplish prominent results at the beginning of their scientific career have an initial advantage over others and increased chances of obtaining further financial support as well as of accomplishing further discoveries[8].

❑ *Technology transfer and commercialisation.* Technology transfer (Coccia, 2004; Coccia & Rolfo, 2002) can be considered as a flow that moves technology (or knowledge in general) from the source (public and private research bodies, universities, etc.) to the users (firms producing goods and services), during a certain time period, by means of provided channels (e.g. communication, logistic, distribution channels). Due to the relevance of technology transfer within the development of economic systems, this phenomenon has been widely studied, which has led to establishment of specialised journals, such as: *Journal of Technology Transfer* of Kluwer Academic Publishers and *International Journal of Technology Transferand Commercialization* born in 2002 by Inderscience publishers.

❑ A main aspect of the scientific research is the *Knowledge Spillovers.* Griliches (1992) explains what knowledge spillovers are, why they are important economic phenomenon, and how they can exist. Jaffe (1989) identifies knowledge created in university research laboratories as an important source of knowledge spillovers. Acs *et al.,* (1994) and, Audretsch & Feldman (1996)

[8] The Matthew effect in science isnamed for the verse in the Gospel according to St. Matthew: *for unto everyone thathathshall be given, and he shallhaveabundance: but from himthathathnotshall be takenawayeventhatwhich he hath* (Matthew, XXV, 29).

provide evidence that large firms are the recipient of knowledge generated in private research laboratories, while small firms benefit more from knowledge spillovers generated at university and public research laboratories. Zucker *et al*., (1998) examine the spillover process and stress the importance of identifiable market exchanges between "Star" scientists and firms.

- *Scientometrics and R&D evaluation.* The assessment of scientific output involves the calculation of indices indicating the production, productivity or impact of research groups (Geisler, 2000). A basic assumption underlying this approach is that scientific progress is made by scientists who group together to study particular research topics and build upon earlier work of their colleagues (de Solla Price, 1963; 1965). In this way, an international community of scientists comes into being, who keep each other informed of results, which need to be published and submitted for evaluation to professional colleagues (Merton, 1972). The production is measured through the number of publications published by scientists in a group. The productivity measure relates his number of publications to the research capacity of the group, which is normally expressed by the number of full time equivalents spent of scientific research (Luwell *et al.,* 1999). Finally, the impact is indicated by indices based on the number of times the publications are cited in some 3,500 international scientific journals covered by the Science Citation Index (SCI), produced by the Institute for Scientific Information (Garfield, 1979). In the bibliometric assessment of technological output, data derived from patents play an important role (e.g., Narin & Olivastro, 1988; Griliches, 1990; Pritchard, 1969). The technical forms of bibliometric analysis are (Broadus, 1987): *Publication counts*; *Citation counts*; *Co-citation analysis* (Small & Griffith, 1974; Tijssen & Leeuw, 1988); *Co-word analysis*, developed in the early 1980's, involves the assigning of keywords to a paper or article by professional readers (Callon *et al.,* 1983; Mullins *et al.,* 1988; Rip & Courtial, 1984); *Scientific mapping* (Healey *et al.,* 1986; Rip, 1988); *Citations in patents* (Collins & Wyatt, 1988). The bibliometric analysis of the field gives rise to a number of problems. Several works of great relevance become common heritage and are, therefore, referred to without specifically quoting them. Moreover, many quotations can be critical rather than positive. Different scientific fields are fostered by groups of different sizes, therefore the chance of being quoted varies greatly from one field to the other. Besides, the value of a scientific work is not always known to its contemporaries (Sirilli, 2000). Other models evaluate the scientific performance of research organizations using combinations of various indicators as well as discriminating analysis techniques (Coccia, 2001; 2004a). Several contributions to this important area of research have been published in two international journals: *R&D Management* by Blackwell publishers, *Research evaluation* (established in 1992) by Beech Tree Publishing and *Scientometrics* (established in 1984) byKluwer Academic Publishers. Moreover, at the International Conference on Bibliometrics, Informetrics and Scientometrics held in Berlin, 11-15 September in 1993 was founded the International Society for Scientometrics and Informetrics. The Society aims to encourage communication and exchange of professional information in the field of scientometrics and informetrics, to improve standards, theory and practice in all areas of the discipline, to stimulate research, education and training, and to enhance the public perception of the discipline. The advancement of the theory, methods and explanations through two main streams: Quantitative Studies, Mathematical, Statistical, and Computational Modelling and Analysis of Information Processes.

- *National and regional system of innovation and scientific knowledge.* The elements that generate and spread knowledge throughout a certain area have been analysed using various approaches, starting from the basic National Systems of Innovation (NSI). Lundvall (1992) was the first scholar to include not only organisations directly involved in the innovative process but also all the aspects of the institutional structure that influence learning, accumulation of knowledge, and the search for all new discoveries. Lundvall's interpretation can be applied, with due adaptations, also to regional and pluri-regional contexts (Braczyk *et al.*, 1998). De Vet (1993) and Ohmae (1995) maintain that, by increasing its degree of globalisation, the economic system pushes interactions among firms into specific sectorial cluster on a more and more regional level. According to a further theoretical elaboration, the complex network of individuals and organisations operating within an innovative system can be described using the model of the *triple helix* (Etzkowitz & Leydesdorff, 1998; 2000). This model brings together three different entities – public research, firms, and the government – which in the past used to be much less integrated or simply associated two by two. Leydesdorff & Etzkowitz (2003) maintain that the public sector can be considered as an element constituting the fourth helix.

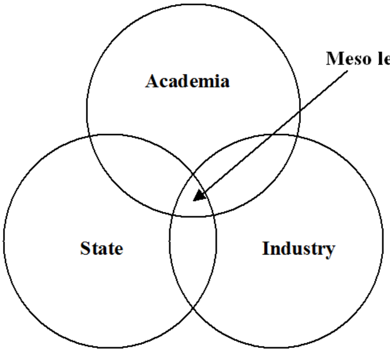


**Figure 3**: *Model of the triple helix describing the relations between Universities/Public Research Bodies – Industry/State. Source: Etzkowitz & Leydesdorff, (1998).*

❑ *Mangerial and organisational behaviour of the R&D Laboratories.* The public sector research is, according to Senker (2001), defined as civil research in institutions for which the major source of funds is public, which are in public ownership or control and which aim to disseminate the results of their research, i.e. the defense research is excluded. Among the entities involved in the production and transfer of scientific research, there are research laboratories and interfaces. Research laboratories are systems that produce goods and services by means of inputs, production processes (of the scientific activity), and outputs (Coccia, 2001), which are absorbed by the users within the economic system, in order to achieve higher competitiveness of the national industrial system, higher social wellbeing, the fulfilment of one's needs, etc.

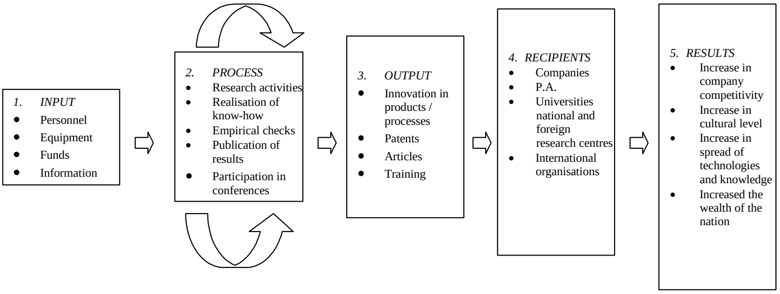


**Figure 4**. *The production system of research bodies.*
**Source:** Coccia, 2001.

*1. Interface subjects* (originated from the intersection of the three sets of the triple helix model) are considered as communication channels that facilitate scientific knowledge transfer from the source to the users by means of resource aggregation (for example, Science and Technology Parks). They also facilitate the meeting of supply and demand of innovations, as seen with Liaison Offices or Offices of Technology Transfer, whose purpose is to *enhance the development and value of University innovations by protecting them and linking them to marketable products and services*. Other studies have tried to elaborate a framework for understanding the structure and behaviour of laboratories that also provides a basis for rationalizing public science and technology policy in order to create laboratories that are more effective. Among the most relevant contributions are those by Bozeman (1982), Bozeman & Crow (1990), and Crow & Bozeman (1998), whose studies focus on research laboratories in the United States, while Coccia's papers (2001, 2004; 2004a) deal mainly with the analysis of Italian public research laboratories.

- *Research and science policy*. A wide overview of research policies in developed countries (Rosenberg, 1994) was drawn up by Ergas (1987), on the basis of the structural features of each national background. The two most relevant types of policies are *mission oriented* and *diffusion oriented*. The former (adopted by the US, UK and France) aims at gaining international leadership by shifting the frontiers of technological possibilities (*technology shifting*), a purpose which is achieved by means of researches targeting radical innovations, supported by high investments in Research and Development for the military sector. *Diffusion oriented* policies (adopted, for example, by Italy and Germany) aim at the so-called *Technological deepening* or movement within the frontier, i.e. scientific research focusing on incremental innovations. These policies are intended to improve the ability to absorb technologies and their commercialisation, by means of funds to secondary education and universities. Justman & Teubal (1996) use the concept of *Technological Infrastructure Policy* (TIP) and consider the public supply of scientific and technological skills as the main element capable of triggering the development of a region and of its industrial sector. This is made possible thanks to the action of the interfaces, which support integration with the sources of knowledge. *Science and public policy* (1974) by Beech Tree Publishing and *Research policy* (1971) by Elsevier are two of the main journals in which papers on this topic are issued.

- *Scientific research and economic growth*. The endogenous growth theory is one of the most prominent developments of research within the macroeconomic field (Nelson & Romer, 1996). Two scholars have greatly contributed to the success of this area of investigation: Romer (1990; 1994), of the University of California, and Lucas (1988), of the University of Chicago. However, cues to this field of research also came from 1970s works by Arrow (1962), of Stanford University, and Uzawa (1965), of Tokyo University. In comparison to the neoclassical growth theory (Solow, 1956), the endogenous growth theory focused primarily on the explanation of the three factors that influence economic growth: technology, labour, and capital. Until that time, growth had been considered exogenous and its causes had not been explained. Lucas and Romer, instead, concentrated on the growth of technology and on how it depends on – i.e. is endogenous to – investments in the field of research, education, and state intervention by means of incentives. This theory has greatly influenced governmental economic policies in a number of industrialised countries, since improvements made to the education system, as well as incentives to firms for research and development activities (Gibbons & Johnston, 1974), are decisive elements for the increase in productivity both of firms and of national innovation systems. These interventions reflect the endogenous growth theory.

## Concluding observations

During its development, economics gave rise to a series of specialised lines of study, among which that of the economics of scientific research, which must be based on the study method of the science that originated it. According to Pareto (1911), the study of economics has the following main purposes: 1) collecting guidelines that will be useful to private individuals and to the public authorities in their economic and social activities; 2) solely aiming at investigating phenomena and their laws. The intention is, in this case, exclusively scientific.

In order to become an autonomous discipline, the economics of scientific research must focus, above all, on the second matter highlighted by Pareto: investigating the laws of the origin of scientific research, of scientific production, of management and organisational behaviour of scientific institutions, leaving issues concerning innovation to other disciplines. It is clear that, by generating inventions and innovations, the process of scientific research creates natural interferences between the two fields of investigation, but they should be kept separate, because research is a phenomenon preceding those of invention and innovation. The economics of scientific research is a branch of economics that investigates the subjects (scientists and institutions) involved in the process of scientific production, in order to provide the means to meet people's and society's needs. Rosenberg's (1974) stress on the problem-solving nature of scientific knowledge, which is echoed by Hicks (1995). If the process of scientific research reaches its goal, it affords the attaining of a greater amount of products with the same costs or the same amount of products with lesser costs, as well as goods for consumption that instruct and entertain the public in general.

The economics of scientific research has made fundamental theoretical and empirical advances in the 1990s. In particular the work of Mansfield (1991, 1995), Narin *et al.,* (1997), Narin & Olivastro (1998), Crow & Bozeman (1998), Hicks & Katz (1997) have shone new light on the economics of scientific research. Scientific research has recently become more and more relevant and is the subject of numerous studies, but it is difficult to investigate because based on a market imperfection due to the absence of prices. Moreover, research is becoming more international, more interdisciplinary, more directed towards application and conducted more by groups and networks of researchers (Gibbons *et al.,* 1994). The objectives of scientific institutions are far more complex than those of firms: universities and public research bodies should maximise prestige, which in turn is a function of other variables that are not easily measured. Several research institutes are public and financed by the government, whose objective is maximising the value added for society. The most difficult matter, when analysing scientific research, is its multidimensional nature, which often leads scholars to use methodological tools borrowed from other disciplines, such as sociology, psychology, industrial organization, and so on. Despite the difficulties scholars have to face when analysing scientific issues, it is hoped that in the future the economics of research shall gain a clearer identity, capable of endorsing its development as an autonomous branch of economics. Its interdisciplinary foundation should be seen as one of its strengths, capable of making the discipline more fertile and allowing for further advancements.

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# 4. Classification of innovation considering technological interaction

## Introduction

Patterns of technological innovation have also been analyzed using analogies with biological phenomena over the last century (Basalla, 1988; Nelson & Winter, 1982; Solé *et al.,* 2013; Sahal, 1981; Veblen, 1904; Wagner, 2011; Ziman, 2000). Wagner & Rosen (2014) argue that the application of Darwinian and evolutionary biological thinking to different research fields has reduced the distance between life sciences and social sciences generating new approaches, such as the evolutionary theory of economic change (Nelson & Winter, 1982; cf., Dosi, 1988). Basalla (1988) suggests the similarity between history of technology and biological evolution. Usher (1954), within these research fields, analyzed the nature of technological processes and the forces that influenced events at technical level (cf., Ruttan, 2001). In general, technological evolution, as biological evolution, displays radiations, stasis, extinctions, and novelty (Valverde *et al.,* 2007).

Scholars of the economics of technical change have tried of defining, explaining and measuring innovation in its many forms as well as of providing classifications of technical change and progress (Asimakopulos & Weldon, 1963; Bigman, 1979; Coccia, 2006; Freeman & Soete, 1987; Pavitt, 1984; Robinson, 1971). As a matter of fact, the study and classification of technological innovations are a central and enduring research theme in the economics of technical change (Bowker, 2000; Jones *et al.,* 2012). Although the concepts of "classification" and "taxonomy" are almost synonyms, they have different meaning. The term taxonomy (from ancient Greek word taxon=arrangement, array) refers to a branch of systematics based on the theory and practice of producing classification schemes with the aim of maximizing the differences among groups. Thus, a taxonomic process provides rules on how to form and represent groups with classification. Instead, classification in science is a product of the taxonomic process that represents classes of entities with a matrix, a table, a dendrogram, etc. (McKelvey, 1982). For instance, the biological classification by Linnaeus, the periodic classification of chemical elements by Mendeleev, the Mercalli scale in seismology, the Beaufort wind force scale, etc. (Coccia, 2006). Taxonomy has usefulness in natural and social sciences if it is able to reduce the complexity of the population studied into simple classes, which are represented by a classification (Archibugi, 2001). In particular, social sciences have two general approaches to create a classification: the empirical and theoretical one (Rich, 1992; Doty & Glick, 1994). Theoretical classifications in social sciences begin by developing a theory of differences which then results in a classification of typologies. The empirical approach begins by gathering data about the entities under study. These data are then processed using statistical techniques to produce groups with measures of similarity (e.g., Minkowski distance, Manhattan distance, Euclidean distance, Weighted Euclidean distance, Mahalanobis distance, Chord distance, etc.).

The subject matter of this study here is taxonomy of technologies. In general, technology studies present severaltaxonomies of technical change (Coccia, 2006; Freeman & Soete, 1987; Pavitt, 1984). However, a taxonomy that considers the interaction between technologies in complex systems is unknown.

This paper here has two goals. The first is to propose a new taxonomy of technologies based on a taxonomic characteristic of interaction between technologies within complex systems. The second is to explain and generalize, whenever possible this theory that may clarify the typologies of interactive technologies that support paths of technological evolution over time. Overall, then, this theoretical framework here can systematize and predict behaviour of interactive technologies and their evolutionary pathways in complex systems, and encourage further theoretical exploration in this *terra incognita* of the interaction between technologies during technological and economic change.

## Theoretical background

Economics of technical change presents many classifications of technological innovation (Coccia, 2006)[9]. De Marchi (2016, p. 983) argues that The Frascati and Oslo manuals assemble technological activities without attempting to propose a cogent organization of the categories. In these research fields, Rosenberg (1982) introduces the distinction between technology directed to new product development, and technology that generates cost reducing–process innovation. Hicks (1932) argued that technological progress is naturally directed to reducing the utilization of a factor that is becoming expansive. Archibugi & Simonetti (1998) suggest that each technological innovation can be classified considering:

1. *Technological nature of innovation* that is a technical description of technological innovation. This classification considers the objects of technological change;
2. *The sector of activity of the producing organization.* This is a classification by subject that promotes technological innovation;
3. *The product group where the innovation is used.* Here, it is considered the economic object of technological innovation;
4. *The using organization.* Here too, as in point 2, it is considered the economic subject of technological innovation;
5. *The human needs* which the technological innovation is designed to address.

Freeman & Soete (1987, pp. 55-62, original italics and emphasis) propose a taxonomy to categorize various types of technical change and distinguish:

> *Incremental Innovations.* These occur more or less continuously in any industry or service activity, although at a varying rate in different industries and over different time periods. They may often occur, as the outcome of improvements suggested by engineers and others directly engaged in the production process, or as a result of initiatives and proposals by users…. They are particularly important in the follow-through period after a radical breakthrough innovation and frequently associated with the scaling up of plant and equipment and quality

[9] For studies of technology and sources of innovation, such as research labs, cf., Calabrese *et al.,* 2005; Cariola & Coccia, 2004; Cavallo *et al.,* 2014, 2014a, 2015; Coccia, 2001, 2003, 2004, 2005, 2005a, 2005b, 2005c, 2006, 2006a, 2007, 2008, 2008a, 2008b, 2009, 2009a, 2010, 2010a, 2010b, 2010c, 2010d, 2010e, 2011, 2012, 2012a, 2012b, 2012c, 2012d, 2013, 2013a, 2014, 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2015, 2015a, 2015b, 2015c, 2015d, 2016, 2016a, 2016b, 2016c, 2017, 2017a, 2017b, 2017c, 2017d, 2018, Coccia & Bozeman, 2016; Coccia & Finardi, 2012, 2013; Coccia & Wang, 2015, 2016; Coccia & Cadario, 2014; Coccia *et al.,* 2015, 2012, Coccia & Rolfo, 2000, 2002, 2009, 2012, 2007, 2010, 2010, 2013; Coccia & Wang, 2015, 2016; Rolfo & Coccia, 2005.

> improvements to products and services for a variety of specific applications. Although their combined effect is extremely important in the growth of productivity, no single incremental innovation has dramatic effects, and they may sometimes pass unnoticed and unrecorded….
> *Radical Innovations.* These are discontinuous events and in recent times is usually the result of a deliberate research and development activity in enterprises and/or in university and government laboratories. They are unevenly distributed over sectors and over time.... big improvements in the cost and quality of existing products.... in terms of their economic impact they are relatively small and localized…. Strictly speaking… radical innovations would constantly require the addition of new rows and columns in an input-output table….
> *New Technological Systems.* Keirstead (1948)… introduced the concept of 'constellations' of innovations, which were technically and economically inter-related. Obvious examples are the clusters of synthetic materials innovations and petrochemical innovations in the thirties, forties and fifties…. They include numerous radical and incremental innovations in both products and processes (Freeman *et al.,* 1982).
> *Changes of 'Techno-Economic Paradigm' (Technological Revolutions).* These are far-reaching and pervasive changes in technology, affecting many (or even all) branches of the economy, as well as giving rise to entirely new sectors. Examples given by Schumpeter were the steam engine and electric power. Characteristic of this type of technical change is that it affects the input cost structure and the conditions of production and distribution for almost every branch of the economy. A change in techno-economic paradigm thus comprises clusters of radical and incremental innovations and embraces several 'new technological systems'.

Sahal (1985, p.64, original Italics) argues that technological innovations can be: "*structural innovations* that arise from a process of differential growth; whereby the parts and the whole of a system do not grow at the same rate. Second, we have what may be called the *material innovations* that are necessitated in an attempt to meet the requisite changes in the criteria of technological construction as a consequence of changes in the scale of the object. Finally, we have what may be called the *systems innovations* that arise from integration of two or more symbiotic technologies in an attempt to simplify the outline of the overall structure". This trilogy can generate the emergence of various techniques including revolutionary innovations in a variety of technological and scientific fields (cf., Sahal, 1981; Coccia, 2016, 2016a).

Abernathy & Clark (1985, p.3) introduce the concept of transilience: "the capacity of an innovation to influence the established systems of production and marketing. Application of the concept results in a categorization of innovation into four types". In particular, the four typologies of innovation by Abernathy & Clark (1985, p.7ff, original italics) are:

> *Architectural innovation*. New technology that departs from established systems of production, and in turn opens up new linkages to markets and users, is characteristic of the creation of new industries as well as the reformation of old ones. Innovation of this sort defines the basic configuration of product and process, and establishes the technical and marketing agendas that will guide subsequent development. In effect, it lays down the architecture of the industry, the broad framework within which competition will occur and develop….
>
> *Innovation in the market niche*…. Opening new market opportunities through the use of existing technology is central to the kind of innovation that they have labelled "Niche Creation", but here the effect on production and technical systems is to conserve and strengthen established designs…. In some instances, niche creation involves a truly trivial change in technology, in which the impact on productive systems and technical knowledge is incremental. But this type of innovation may also appear in concert with significant new product introductions, vigorous competition on the basis of features, technical refinements, and even technological shifts. The important point is that these changes build on established technical competence, and improve its applicability in emerging market segments….
>
> *Regular innovation*…. is often almost invisible, yet can have a dramatic cumulative effect on product cost and performance. Regular innovation involves change that builds on established technical and production competence and that is applied to existing markets and customers. The effect of these changes is to entrench existing skills and resources…. can have dramatic effect on production costs, reliability and performance…. Regular innovation can have a significant effect on product characteristics and thus can serve to strengthen and entrench not only competence in production, but linkages to customers and markets….
>
> *Revolution innovation.* Innovation that disrupts and renders established technical and production competence obsolete, yet is applied to existing markets and customers…. The reciprocating engine in aircraft, vacuum tubes, and mechanical calculators are recent examples of established

technologies that have been over thrown through a revolutionary design. Yet the classic case of revolutionary innovation is the competitive duel between Ford and GM in the late 1920s and early 1930s.

Anderson & Tushman (1986) distinguish, in patterns of technological innovation, two types of discontinuous change: competence-enhancing and competence-destroying discontinuities. Competence-enhancing discontinuities are based on existing skills and know-how. Competence-destroying discontinuities, instead, require fundamentally new skills and cause obsolescence of existing products and knowledge. In general, technological shifts are due toboth competence-destroying and competence-enhancing because some firms can either destroy or enhance the competence existing in industries (*cf.,* Tushman & Anderson, 1986). Usher (1954), in this context, argues that technological innovation is driven by a cumulative significance in the inventive process (cf., Rosenberg, 1982).

Grodal *et al.,* (2015), in management of technology, propose that the evolution of both technological designs and categories follows a similar pattern, characterized by an early period of divergence followed by a period of convergence. Grodal *et al.,* (2015, p. 426) identify the following mechanisms within coevolutionary processes of technology:

- Design recombination is the creative synthesis of two or more previously separate designs that results in the creation of a new design to address an existing or potential need.
- Path dependence is the mechanism through which the cumulative effects of prior technological design choices increasingly determine and constrain subsequent design recombinations.
- Design competition is the mechanism by which producers and users make design investment choices about which designs to retain and which to abandon.

Garcia & Calantone (2002) apply Boolean logic to identify three labels in product innovation management: radical, really new and incremental innovation. The radical innovations cause discontinuity of marketing and technology, both at a macro and a micro level. Incremental innovations occur only at micro level and cause either discontinuity of marketing, or discontinuity of technology, but not both. Really new innovations include combinations of these two extremes. These three definitions of product innovation also indicatea reduction in the degree of innovativeness as follows: radical$\rightarrow$ really new $\rightarrow$ incremental innovation.

An alternative approach to categorize technical change is the scale of technological innovation intensity by Coccia (2005) that measures and classifies technical change according to effects generated by technological innovations on geo-economic space, in analogy with the effects of seismic waves (cf., also Coccia, 2005a).

Pavitt (1984, p.343ff) proposed a taxonomy of sectoral patterns of technical change based on innovating firms: "(1) supplier dominated; (2) production intensive; (3) science based. They can be explained by sources of technology, requirements of users and possibilities for appropriation. This explanation has implications for our understanding of the sources and directions of technical change, firms' diversification behaviour, the dynamic relationship between technology and industrial structure, and the formation of technological skills and advantages at the level of the firm, the region and the country".

De Marchi (2016, p.984), instead, suggests a classification based on general characteristics of scientific discovery and technological innovation. The features of these two activities can be described with oppositions between pairings of aspects of ''real oppositions'', graphically represented by pairs of semi axes. The first real opposition would be between problems and solutions. The second real opposition adopted is that countering specificity and generality of problems and solutions (cf., Arthur, 2009). Since these two oppositions are simultaneously applicable to science and technology, the study categorizes the activities of both research and innovation in a matrix 2×2, where each cell is defined by a pair of semi axes (cf., De Marchi, 2016, pp. 984-985).

In short, the vast literature has suggested many approaches for classification of innovation, though studies described above are not a comprehensive review in these research fields (Clark, 1985; Coccia, 2016; Hargadon, 2003; Nelson & Winter, 1982; Nelson 2008; Rosenberg, 1969; cf., Anadon *et al.,* 2016)[10]. However, studies of technical change have given little systematic attention to the different characteristics of interaction between technologies that can generate coevolution of technological systems and technological change in society. The crux of the study here is to categorize technologies considering their interaction with other technologies, in a broad analogy with the ecology[11]. The suggested

10 See Coccia (2006) for further approaches of classifications of innovation in economics of technical change and management of technology.

11 Ecology is the scientific study of interactions between organisms of the same or different species, and between organisms and their non-living environment (Poulin, 2006). The scope of the ecology is to explain the number and distribution of organisms over time and space and all sorts of interactions.

interpretation here can provide a theoretical framework to clarify typologies of interactive technologies that support evolutionary pathways of complex systems of technology over time and space. At the same time, we are aware of the vast differences between biological and technological processes (cf., Braun, 1990; Hodgson, 2002; Ziman, 2000).

## Study Design

In order to lay the foundations for a new taxonomy of technologies here, it is important to clarify the concept of complexity and complex systems. Simon (1962, p.468) states that: "a complex system [is]… one made up of a large number of parts that interact in a non simple way…. complexity frequently takes the form of hierarchy, and…. a hierarchic system… is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem." McNerney *et al.,* (2011, p. 9008) argue that: "The technology can be decomposed into $n$ components, each of which interacts with a cluster of $d$–1 other components" (cf., Arthur, 2009). A characteristic of complex systems is the interaction *between* systems and the interaction *within* systems—i.e., among the parts of those systems. This philosophical background of the architecture of complexity by Simon (1982), shortly described, is important to support theoretically the taxonomy of interactive technologies proposed by the study here.

Taxonomy of interactive technologies is based on following concepts:

* A technology is a complex system that is composed of more than one component or sub-system and a relationship that holds between each component and at least one other element in the set. The technology is selected and adapted in the Environment $E$ with a natural selection operated by market forces and artificial selection operated by human beings to satisfy needs, achieve goals and/or solve problems in human society.

* Interaction between technologies $T1$ and $T2$ or more associated technologies $Ti$ ($i$=1, …, n) is a reciprocal adaptation between technologies in a complex system $S$ with inter-relationships of information/resources/energy and other physical phenomena to satisfy needs, achieve goals and/or solve problems in human society. $Ti$ is called interactive technology in S.

The proposed taxonomy (TX) here is established to respect the following conditions of (Brandon, 1978, pp. 188-192):

i. independence: the taxonomy to play its explanatory role cannot be a tautology.

ii. generality: it must apply to the whole elements of technological change. It must be general and universally applicable throughout the domain of technical and economic change.

iii. epistemological applicability: TX has to be testable and can be applied to particular cases of systems of technology.

iv. and empirical correctness: TX must not be false.

Overall, then, the taxonomy suggested here has the goal to categorize and generalize the typologies of interactive technologies and clarify, whenever possible their role in evolutionary pathways of complex systems over time and space.

## A proposed classification of interactive technologies in complex systems

The basic unit of technology analysis, in the proposed taxonomy and theory, is interactive technologies. In general, technologies do not function as independent systems *per se*, but they depend on other (host) technologies to form a complex system of parts that interact in a non-simple way (*e.g.,* batteries and antennas in mobile devices, etc.; cf., Coccia, 2017). Coccia (2017a) states the theorem of *not* independence of *any* technology that in the long run, the behaviour and evolution of *any* technology is *not* independent from the behaviour and evolution of the other technologies. In general, technologies are not autonomous systems *per se*, but they form complex systems composed of inclusive and interrelated sub-systems of technologies until the lowest level of technological unit (*cf.,* Simon, 1962, p. 468; Oswalt, 1976; cf., Coccia, 2017, 2017a). To put it differently, technologies can function in ecological niches of other technologies and the interaction between technologies can be an important taxonomic characteristic to categorize technologies that support the coevolution of technological systems (i.e., the evolution of reciprocal adaptations of technologies in a complex system S).

Suppose that the simplest possible case involves only two interactive technologies, *T1* and *T2* in a Complex System *S*(T1, T2); of course, the theory can be generalized for complex systems including many sub-systems of technology, such as *S*(T1, T2, …, T*i*, …$T_N$). Table 1, based on theoretical framework above, categorizes four types of interactive technologies within a complex system S, in a broad analogy with ecology.

**Table 1.** *A classification of technologies in complex systems*

| Grade | Typology of interactive technology | Examples |
|---|---|---|
| 1 | *Technological parasitism* is a relationship between two technologies T1 and T2 in a complex system S where one technology T1 benefits (+) from the interaction with T2, whereas T2 has a negative side (–) from interaction with T1. The interaction between T1 and T2 in mathematical symbols is indicated here (+, –) to represent the benefits (positive or negative) to technologies from interaction in a complex system S(T1,T2). | An example of parasite technology is audio headphones, speakers, software apps, etc. of many electronic devices. These technologies are parasites of different technologies because they can function, if and only if (iff) associated with other technologies. Plus sign (+) indicates the fruitful benefit to parasitic technologies from interaction. In Information and Communication Technologies, host technology decreases its energy from interaction with parasitic technologies, such as electric power of battery; the sign –(minus) here indicates the negative side of interaction for host technology. |
| 2 | *Technological commensalism* is a relationship between two technologies where one technology T1 benefits (+) from the other without affecting it (0). The commensal relation is often between a larger host or master technology and a smaller commensal technology; host or master technology is unmodified from this interaction, whereas commensal technologies may show great structural adaptation consonant with their systems. The interactive technologies (T1, T2) have a relation (+, 0) in a complex system S. 0 (zero) indicates here no benefits from interaction. | An example of commensal technologies is the connection of a single mobile device to a large Wi-Fi network; the connection of an electric appliance to national electricity network; etc. |
| 3 | *Technological mutualism* is a relationship in which each technology benefits from the activity of the other technology. The interaction between T1 and T2 has mutual benefits in S indicated with symbols (+, +). | An example of mutual technologies is the relation between battery and mobile devices, antenna and mobile devices, HD displays and mobile devices, etc. The interaction here generates mutual benefits between technologies (+,+) in S. |
| 4 | *Technological symbiosis* is a long-term interaction between two technologies (T1,T2) that evolve together in a complex system S. The symbiotic technologies have a long-run interaction that generates continuous and mutual benefits and, as a consequence, coevolution of complex systems in which these technologies function and adapt themselves. The interaction between T1 and T2 in S is indicated with (++, ++) to represent benefits of the long-run mutual symbiotic relationship between host and parasitic technologies (coevolution of technological systems). | For instance, symbiotic technologies are the continuous interaction between Bluetooth technology and mobile devices that has improved both technologies and increased their effectiveness and technical performance, such as Bluetooth 2.0 with an Enhanced Data Rate for faster data transfer, Bluetooth 4.0 with low energy to save battery of mobile devices, etc. This technological evolution of Bluetooth technology is associated with new generations of mobile devices–e.g. *i*Phone 6,7,8, etc.– in order to better interact with this and other technologies and generate coevolution of complex systems in which these technologies function (Apple Inc., 2016; Bluetooth, 2017). |

**Note:** +(Plus) is a positive benefit to technology T$i$ from interaction with technology T$j$ in a complex system S($\forall i=1,\ldots,n;\ \forall j=1,\ldots,m$); –(minus) is a negative benefit to technology T$i$ from interaction with technology T$j$ in S; 0 (zero) indicates a neutral effect from interaction between technologies T$i$ and T$j$ in S; ++ is a strong positive benefit from long-run mutual symbiotic interaction between technologies T$i$ and T$j$ in S (i.e., coevolution of T$i$ and T$j$ in S).

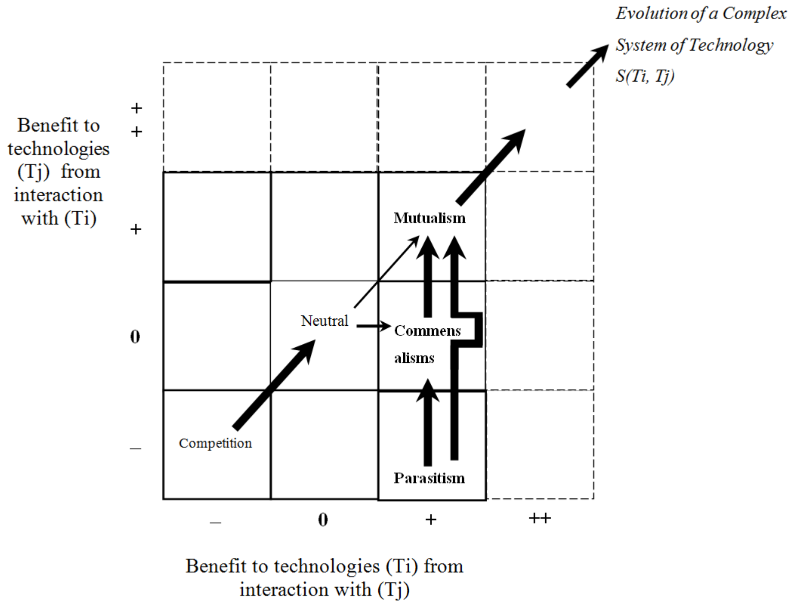


**Figure1.** Types and evolutionary pathways of interactive technologies in a complex system S.

**Note.** The notions of positive, negative and neutral benefit from interaction between technologies *Ti* and *Tj* in S are represented with mathematical symbols +, –, 0 (zero), ++ is a strong positive benefit from long-run mutual symbiotic interaction between technologies T*i* and T*j* in S (i.e., coevolution of T*i* and T*j* in S). Thick solid arrows indicate the probable evolutionary route of interactive technologies in a complex system S: the possibilities for parasitic technologies to become commensals, mutualists, and symbiotic; thin arrows show other possible evolutionary pathways of technologies T*i* and T*j* during the interaction in a complex system S( $\forall i=1,\ldots,n;\ \forall j=1,\ldots,m$).

In general, parasitism, mutualism, commensalism and symbiosis between technologies do not establish clear cut-offs of these concepts and each relationship represents an end-point of an evolutionary development of interactive technologiesin a complex system *S*(cf., Poulin, 2006 for ecological interaction). In particular, parasitism is an interaction that may evolve over time towards commensalism, mutualism and symbiosis to support evolutionary innovations (cf., Price, 1991). The symbiosis is also increasingly recognized as an important selective force behind interdependent coevolution of complex systems (cf., Smith, 1991). In short, the interaction between technologies tends to generate stepwise coevolutionary processes of complex systems (cf., Price, 1991). Figure 1 represents evolutionary pathways of the four typologies of interactive technologies in S (Table 1).

The proposed taxonomy here has the following properties:

1). *Property of increasing interaction of technology in S over time.* Interactive technologies increase the grade of interaction over time directed to evolution of an overall system of technology S along the following evolutionary route: technological parasitism→ commensalism → mutualism → technological symbiosis ⇒ evolution of technology (see, Figure 1).

2) *Property of inclusion of interactive technologies.* Interactive technologies can be of four types (Tab. 1):

TS= Technological Symbiosis; TM= Technological Mutualism; TC=Technological Commensalism; TP= Technological Parasitism.

TS, TM, TC and TP are sets within a complex system S.

The set theory indicates with the symbol $\subset$ a subset. A derived binary relation between two sets is the set inclusion. In particular, interactive technologies of proposed taxonomy have the following property of inclusion in S:

$[(TP \subset TC) \subset TM] \subset TS$ ■

Overall, then, this taxonomy can systematize the typologies of interactive technologies and predicts their evolutionary pathways that generate stepwise coevolutionary processes within a system of technology S (e.g., devices, new products, etc.).

## Predictions based on interactive technologies

Technologies are complex systems composed of interrelated technological subsystems until the lowest level of technological unit (cf., Oswalt, 1976). Interaction is proposed here to be one of the mechanisms driving the evolution of technology and a critical taxonomic characteristic for a classification of technology (cf., Coccia, 2017). On the basis of the suggested taxonomy here, it is possible to make some predictions about evolutionary paths of interactive technologies within complex systems S.

a) The short-run behaviour and evolution of interactive technologies is approximately independent from the other technologies in S. In particular, the short-run evolution of a specific interactive technology (e.g., parasite technology) is due to advances or mutations in the technology itself.

b) The long-run behaviour and evolution of any interactive technologies (i.e., *technological parasitism, commensalism, mutualism and symbiosis*) depends on the behaviour and evolution of associated technologies; in particular, the long-run behaviour and evolution of any interactive technology is due to interaction with other technologies within and between complex systems.

c) Symbiotic, mutualistic, commensal and parasitic technologies tend to generate a rapidevolution of a complex system of technology S in comparison with complex systems without interactive technologies.

## Discussion

The proposed taxonomy and theory here have a number of implications for the analysis of nature, source and evolution of technical change. Some of the most obvious implications, without pretending to be comprehensive are as follows.

### Contribution to the literature on taxonomy of technical change

This study contributes to the literature on taxonomy of technical change by detailing the importance of specific typologies of interactive technologies during the evolutionary patterns of technological innovation. Current literature categorizes technical change with *static* characteristic considering objects and/or subjects of technological innovation (Archibugi & Simonetti, 1998; Freeman & Soete, 1987). In fact, technology can be classified according to: a) the nature of technological innovation-*object*-, such as incremental and radical innovation, product and process innovation, etc. (cf., Freeman & Soete, 1987); b) The sector of activity of innovative firms-*subject*-, such as supplier-dominated, scale-intensive, specialized suppliers and science- based (Pavitt, 1984).

The study here extends this specific literature by identifying typologies of technologies with a *dynamic* characteristic represented by interaction between technologies in complex systems over time. The theoretical framework here categorizes the interaction between technologies in technological parasitism, commensalism, mutualism and symbiosis. These typologies of interactive technologies have specific characteristics that drive the evolutionary pathways of complex systems of technology and technological diversification over time and space. The dynamic characteristic underlying the proposed taxonomy here may also help better understand the linkages between technologies that explain directions of technical development of complex systems of technology. In general, the taxonomy and theory here, borrowing concepts from ecology, it can extend economics of technical change with a new research stream to theorize and categorize interactive technologies that can explain the process through which these technologies become meaningful, and their role for processes of evolution of complex systems of technology.

### Contribution to the literature on evolution of technology

This theory here also extends the literature on technological evolution identifying some important but overlooked typologies of technology within the nature of technology (Arthur, 2009; Dosi, 1988). Arthur (2009, pp.18-19) argues that the evolution in technology is due to combinatorial evolution: "Technologies somehow must come into being as fresh combinations of what already exists". This combination of components and assemblies is organized into systems to some human purpose and has a hierarchical and recursive structure: "technologies … consist of component building blocks that are also technologies, and these consist of subparts that are also technologies, in a repeating (or recurring) pattern" (Arthur, 2009, p.38). In short, Arthur (2009) claims that a source of change in technology evolution is the combination based on supply of new technologies assembling existing components and on demand for means to fulfil purposes, the need for novel technologies. The suggested taxonomy of technologies here is consistent with this well-established literature by Arthur (2009) as well as with studies that consider structural innovations and systems innovations based on integration of two or more symbiotic technologies (Sahal, 1985). However, the study here extends this research field by detailing how different typologies of technologies interact in complex systems and guide the evolution of technology. One of the most important implications of this work is also that specific interactive technologies, such as symbiotic technologies, can generate fruitful evolutionary routes for complex systems of technology S in evolving industries. Kalogerakis *et al.,* (2010, p. 418) argue that new technology can also be due to 'inventive analogical transfer' from experience of a specific technology in one knowledge field – *source domain* – to other scientific fields – *target domains*. This theory adds to this body of literature a new perspective represented by the interaction between technologies from source domain to other target domains of systems of technology to satisfy needs and/or to solve problems in human society. *Overall, then, the theoretical framework developed here opens the black box of the interaction between technologies that affects, with different types of technologies, the evolutionary pathways of complex systems of technology over time and space.*

## Concluding remarks

Manifold dimensions in the analysis and evolution of technology are hardly known. Researchers should be ready to open the debate regarding the nature and types of interaction between technologies that may explain the evolution of technology and technical change in human society (cf., De Marchi, 2016). Some scholars argue that technologies and technological change display numerous life-like features, suggesting a deep connection with biological evolution (Basalla, 1988; Erwin & Krakauer, 2004; Solé *et al.,* 2011; Wagner & Rosen, 2014). This study extends the broad analogy between technological and biological evolution to more specifically focus on the potential of a taxonomy and theory of interactive technologies in complex systems, but fully acknowledge that interaction between technologies is not a perfect analogy of biological/ecological interaction; of course, there are differences (Ziman, 2000; Jacob, 1977; Solé *et al.,* 2013). For studying technical change, though, the analogy with biology and ecology is a source of inspiration and ideas because it has been studied in such depth and provides a logical structure of scientific inquiry in these research fields. The study here proposes a taxonomy of technology based on four typologies represented by technological parasitism, commensalism, mutualism and symbiosis that can guide evolutionary pathways of technology within and between complex systems. These types of interactive technologies seem to be general driving components for the evolution of new technology across time and space (cf., Smith, 1991; Prince, 1991; Coccia, 2017). The characteristics and dynamics of interactive technologies, described in table 1 and figure 1, are also affected by learning processes and technological capability of firms in markets with rapid change (cf., Teece *et al.,* 1997; Zollo & Winter, 2002).

On the basis of arguments presented in this study, the taxonomy here categorizes general typologies of interactive technologies that can explain, whenever possible, some characteristics of the interaction between technologies for the evolution of complex systems of technology and technical change in human society.

In particular, the results here suggest that:

1. Technological parasitism, commensalism, mutualism and symbiosis can help explain aspects of evolutionary pathways of complex systems within technical change in society.
2. Evolution of complex systems of technology may be rapid in the presence of subsystems of technological symbiosis and/or mutualism, rather than technological parasitism and commensalism (*see*, Fig. 1).

Hence, the study here provides an appropriate theoretical framework to classify interactive technologies and explain possible evolutionary pathways of complex systems of technology. Moreover, taxonomy here suggests a general prediction that it may be possible to influence (support) the long-run evolution of technical change by increasing mutual symbiotic interactions between technologies. This finding could aid technology policy and management of technology to design best practices to support technological interaction in complex systems for industrial and economic change, and technological progress of human society. Valverde (2016, p.5) in this context also states that: "Technological progress is associated with more complex human-machine interactions". As a matter of fact, human activity acts as ecosystem engineers able to change social and technological systems (Solé *et al.,* 2013).

In short, the study here makes a unique contribution, by showing how technology can be classified in critical typologies considering the concept of interaction between technologies. This idea of a "taxonomy of interactive technologies" suggested in the study here is adequate in some cases but less in others because of the vast diversity of technologies and their interaction in complex systems and environments. Nevertheless, the analogy keeps its validity in classifying and explaining general interaction and coevolution of technology in complex systems. The taxonomy here also suggests some properties of interactive technologies that are a reasonable starting point for understanding the universal features of the technology and coevolution of complex systems of technology that leads to technical change and progress in society, though the model here of course cannot predict any given characteristics of technologies with precision.

These typologies of interactive technologies can create theoretically, methodological and empirical challenges. In particular, scholars studying technology and technological evolution might have to take the interaction between technologies into account and begin data collection to explain with comprehensive model the role of interactive technologies for the emergence and evolution of technological paradigms and trajectories (Nelson & Winter, 1982; Dosi, 1988). Future efforts in this research stream will be directed to provide empirical evidence of the interaction between technologies in complex systems to better classify and evaluate their role during the process of evolution of new technology and, in general, of technical change. Other directions for the future of this research topic, which is not a studied field, are: firstly, the proposed taxonomy needs to be tested on the basis of complete coverage of different technologies belonging to many sectors; secondly, this taxonomy needs to be extended; thirdly, the taxonomy may be studied to provide a variety of uses for designing best-practices of innovation policy and management of technology; finally, the taxonomy and the theory here may be studied to shed light on a number of important aspects of technical change, such as new types, directions and routes of interactive technologies in different industries, accumulation of technological skills and dynamic capabilities of firms from interaction between technologies in markets with rapid change, emerging technologies from interactive technologies, etc. (cf., Teece *et al.,* 1997).

Overall, then, this taxonomy may support a better understanding of the role played by interactive technologies in evolutionary patterns of technological innovation and in general social and technical change. In addition, given the variety of technologies in current patterns of technological change, the taxonomy here can support a generalization and systematization of typologies of interactive technologies during the evolution of technology. Although, we know that other things are often not equal over time and space in the domain of technology.

To conclude, the proposed taxonomy here based on the ecology-like interaction between technologies—may lay the foundation for development of more sophisticated concepts and theoretical frameworks in economics of technical change. In particular, this study constitutes an initial significant step in categorizing technologies considering the interaction between technologies in complex systems and evolution of technology inexorably interlinked. However, identifying generalizable taxonomy and theory is a non-trivial exercise. Wright (1997, p. 1562) properly claims that: "In the world of technological change, bounded rationality is the rule."

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# 5. Theorem of not independence of any technological innovation

## Introduction

In analogy with some concepts from systems science (Ackoff, 1971, p. 661ff; *cf.*, Churchman & Ackoff, 1950; Oppenheimer, 1958; Rosenblueth *et al.,* 1943), suppose that: Technological innovation is defined an entity (system) that is composed of at least two components and a relation that holds between each of its components and at least one other element in the set. Each of a technological innovation's components is connected to every other component, directly or indirectly. No subset of components in a technology is unrelated to any other subset.

*Remark*: a component of technology is an element of its system that can be abstract or concrete. Abstract components of technology are concepts, such as in computer programming, a string. Concrete (tangible) components of technology are objects, such as electronic and/or mechanical parts of artifacts (cf., Ackoff, 1971).

In this context, the technology has fundamental interactions between components (sub-systems) and other associated systems (technological innovations) in a complex system; these fundamental interactions are reciprocal movement of information/resources/energy and other physical phenomena directed to satisfy needs, achieve goals and/or solve problems of human society. The fundamental interaction in technological domains is strong between intra-component linkages (sub-systems) and weak between inter-component linkages of one or more technological innovations (Simon, 1962). The environment of a technological innovation is a set of elements and factors that can affect its state. The state of a technological innovation "at a moment of time is the set of relevant properties which that system has at that time" (Ackoff, 1971). For instance, environments of technology are the markets (competition, oligopoly, monopolistic competition, contestable, etc.) that can drive technological advances with a reciprocal influence between innovations in order to achieve and/or support goals and competitive advantage of subjects (competition-driven innovation).

Some characteristics of technological innovations are:

1. A technological innovation can be a state-maintaining system: "is one that (1) can react in only one way to any one external or internal event but (2) it reacts differently to different external or internal events, and (3) these different reactions produce the same external or internal state (outcome). Such a system …must be able to *discriminate* between different internal or external states to changes in which it reacts". These technological innovations: "are not capable of learning because they cannot choose their behavior. They cannot improve with experience." (e.g., compass; Ackoff, 1971, p.665, original italics).
2. A goal-seeking technological innovation is a system:"that can respond differently to one or more different external or internal events in one or more different external or internal states and that can respond differently to a particular event in an unchanging environment until it produces a particular state (outcome)…Thus such a system has a *choice* of behavior… Under constant conditions a goal-seeking system may be able to accomplish the same thing in different ways and it may be able to do so under different conditions. If it has memory, it can increase its efficiency over time in producing the outcome that is its goal ...for example, an electronic maze-solving rat.... Systems with automatic 'pilots' are goal-seeking." (Ackoff, 1971, pp.665-666, original emphasis).
3. A multi-goal-seeking technological innovation isa system: "that is goal-seeking in each of two or more different (initial) external or internal states, and which seeks different goals in at least two different states, the goal being determined by the initial state" (Ackoff, 1971, pp.666).
4. A purposive technological innovation: "is a multi-goal-seeking system the different goals of which have a common property. These types of system can pursue different goals but they do not select the goal to be pursued.... A computer which is programmed to play more than one game ...is multi-goal-seeking. What game it plays is not a matter of its choice,

however; it is usually determined by an instruction from an external source. Such a system is also purposive because 'game winning' is a common property of the different goals which it seeks” (Ackoff, 1971, pp.666). In short, by combining two or more goal-seeking components, it is possible to construct a multi-goal-seeking (and hence a purposive) system.

5. A purposeful system, instead, is: “one which can produce the same outcome in different ways in the same (internal or external) state and can produce different outcomes in the same and different states. Thus a purposeful system is one which can change its goals under constant conditions; it selects ends as well as means and thus displays *will*. Human beings are the most familiar examples of such systems …The goal of a purposeful system in a particular situation is a preferred outcome that can be obtained within a specified time period. The objective of a purposeful system in a particular situation is a preferred outcome that... can be obtained over a longer time period.” (Ackoff, 1971, pp.666-667, original italics).
6. A technological innovation can be state-maintaining, goal-seeking, multi-goal-seeking, or purposive; but not a purposeful system.

## Theorem of *Not* independence of *Any* technological innovation

In the long run, the behavior and evolution of *any* technological innovation $\varphi_i$ is *not* independent from the behavior and evolution of the other technological innovations $\lambda_j \forall i = 1, \ldots, n \text{ and } j = 1, \ldots, m$

*1 Proof*

Assume the statement of the theorem above (called P) to be false.

Suppose that $\neg P$ (the negation of the theorem) is true: $\exists$ a technological innovation $\varphi_i$ such that (s.t.) $\varphi_i$ is independent from the other technological innovations $\lambda_j$

$\Rightarrow \exists$ a technological innovation $\varphi_i$ s.t. it is a purposeful system that can change its goals, select ends as well as means and displays will.

However, *any* technological innovation cannot be a purposeful system per definition.

The statement $\neg P$ implies a contradictory assertion (an *argumentum ad absurdum*: reduction to absurdity).

Therefore, $\therefore$ the statement P (theorem) is true (QED).

*2 Corollary*

- ∄*any* technological innovation $\varphi_I$ that has a long-run behavior and evolution independent from the other technological innovations $\lambda_j$.
- The theoretical implications of this theorem are fundamental interactions between systems of technologies that generate dependence and interdependence between two or more associated technologies in human society.

## Theoretical and practical implications of the theorem

The concept system, applied here, plays a critical role in science and technology (Ackoff, 1971). The systems approach focuses on systems taken as a whole, not on their parts taken separately and is an appropriate theoretical framework to analyze the patterns and evolution of technological innovation (Coccia, 2017). The theoretical implication of this theorem is that:

1. in the long run, the behavior and evolution of any one of the technological innovations interact and depend on the behavior and evolution of the other technological innovations;
2. in the short-run, the behavior and evolution of technological innovations may be approximately independent of the short-run behavior and evolution of the other technological innovations (cf., Simon, 1962).

The theorem here can explain and generalize, whenever possible the existence of fundamental interactions, between *any* technological innovations and at least one other technological innovations in complex and inter-related systems. The not independence of any technology is an important property of the evolution of technology inhuman societies.

Overall, then, this theory here suggests that in the long run, *any* technological innovation does not function as independent system *per se*, but technological innovations depend on the other technological innovations to form elements of complex systems that interact and coevolve in a non-simple way. Technology has an intrinsic nature to progress with fundamental interactions with the other technological innovations and human societies (human-technology interactions) to satisfy needs, achieve goals and/or solve problems. Future technological and scientific progress may generate, with the artificial intelligence (AI), new technology similar to purposeful systems, but the similarity will not be an identity and a completely independence of AI technology is hard to be conceived.

To conclude, the proposed theorem here may form a groundwork for development of more sophisticated theoretical framework sto explain the evolution of technology in the long run. However, we know that other things are often not equal over time and space in the domain of technology. There is need for much more detailed research to shed further theoretical and empirical light on patterns of technological innovation to explain evolution of technology, technological and economic change in human society.

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# 6. The Fishbone Diagram to identify, systematize and analyze the sources of general purpose technologies

## Introduction

Technological progress has a great weight in supporting patterns of economic growth over the long run (Helpman, 1998; Coccia, 2005b; 2007; 2009a; 2010a; 2010b; Ruttan, 2001; Rosenberg, 1982). A main element of the technical progress is the path-breaking innovations, which make prior technical knowledge obsolete and sustain industrial change (Sahal, 1981; Colombo *et al.,* 2015). A path-breaking innovation is the General Purpose Technology (GPT), which is one of the contributing factors of the long-run technological and economic change in society (Bresnahan, 2010). The GPTs are enabling technologies for a pervasive use in many sectors to foster new products and processes (Helpman, 1998). The GPTs generate changes of techno-economic paradigm ("Technological Revolutions"), which affect almost every branch of the economy (Freeman & Soete, 1987: 56-57) and support the "secular process of growth" (Bresnahan & Trajtenberg, 1995: 83; *cf.* Helpman, 1998; Lipsey *et al.,* 1998). Ruttan (2006) argues that GPT is basic to sustain productivity and economic growth of nations over time.

The driving forces of GPTs are different from those that support other innovations of less intensity (Helpman, 1998; Ruttan, 1997; Lipsey *et al.,* 1998, Coccia, 2005, 2005a; 2010, 2014, 2014a; 2015; Schultz & Joutz, 2010). Scholars have described several approaches to explain the source of technical change and technological evolution (*cf.* Wright, 1997; Hall & Rosenberg, 2010; Helpman, 1998:. 2; Coccia, 2015; Wang *et al.,* 2016; Li, 2015; Robinson *et al.,* 2007; von Hippel, 1988), however, an appropriate visualization technique for identifying and analyzing the potential root causes of general purpose technologies (GPTs) is hardly known. In particular, a problem is to represent in a comprehensive theoretical framework the several drivers of General Purpose Technologies (GPTs) that support the technological evolution for technological and economic change in society over the long run (*cf.* Ruttan, 1997; 2006).

The study here confronts this scientific problem by using a graphical representation with the fishbone diagram, which seems to be an appropriate visualization technique for categorizing and analyzing the complex determinants of the technological evolution of GPTs over time. The main aim of this study is therefore to provide a novel graphical representation to explore whenever possible, the potential root causes of the source and evolution of general purpose technologies (GPTs) that explain the economic change in society.

## Conceptual grounding

General Purpose Technologies (GPTs) are revolutionary changes from current technological trajectories (Bresnahan, 2010:763-791). These path-breaking innovations are mainly of transformative nature and generate a "destructive creation" (Calvano, 2007), which makes prior products and knowledge obsolete (*cf.* Colombo *et al.,* 2015). Lipsey and colleagues (1998:43) define the General Purpose Technology: "a technology that initially has much scope for improvement and eventually comes to be widely used, to have many users, and to have many Hicksian and technological complementarities". GPTs are enabling technologies that exert a pervasive impact across firms, industries and that permeate the overall structure of the economy (Coccia, 2005, 2010a). The diffusion of GPTs is by several ripples of effects that remove barriers and generate significant techno-economic change in society with new communications and transportation technology. Coccia (2005) classifies the GPTs, in the scale of innovation intensity with the highest degree of socio-economic impact. In particular, Coccia (2005, pp. 123-124) claims, referring to revolutionary innovations, such as GPTs, that:

> The means of human communication are radically changed and a new means of communication, which heavily affects all the economic subjects and objects, is born, forcing all those who use it to change their habits. A new technoeconomic paradigm is born… The propulsive capacity for development offered by seventh-degree innovation is so high that it hauls the entire economy.

> Thanks to the new methods of communication, there is also greater territorial, social, and human integration. Another characteristic of seventh-degree innovations is the ease of their spread. The mobility of people, goods, capital, and information increases and the time taken to travel and communicate is reduced.

Bresnahan & Trajtenberg (1995: 86-87) show that GPTs have a treelike structure with basic new technology located at the top of the tree and all derived technologies, for several industries, radiating out towards every branch of the economy. In fact, the General Purpose Technologies generate clusters of new technology in several industries because they are general mechanisms and/or components and/or infrastructure for the architecture of various families of products/processes that are made quite differently. The different applications of new GPTs are driven by firms to maximize the profit and/or to exploit the position of a (temporary) monopoly in different sectors and industries over time (Coccia, 2015).

In general, GPTs are characterized by pervasiveness, inherent potential for technical improvements, and 'innovational complementarities', giving rise to increasing returns-to-scale, such as the steam engine, the electric motor, and semiconductors (Bresnahan & Trajtenberg, 1995: 83, original emphasis)[12]. Jovanovic & Rousseau (2005: 1185) show that the distinguishing characteristics of a general purpose technology are: (1) *Pervasiveness*: "The GPT should spread to most sectors". It has an impact on technical change and productivity growth across a large number of industries; (2) *Improvement*: "The GPT should get better over time and, hence, should keep lowering the costs of its users". It should lead to sustained productivity growth and cost reductions in several industries; (3) *Innovation spawning*: "The GPT should make it easier to invent and produce new products and processes" (*cf.*, Bresnahan & Trajtenberg, 1995). Lipsey *et al.*, (1998: 38) describe other main characteristics of GPTs, such as: the scope for improvement, wide variety and range of uses during its evolution and strong complementarities with existing or potential new technologies. Another main feature of GPTs is a long-run period between their initial emergence as invention and final commercial introduction in new products (Lipsey *et al.*, 1998; 2005). Rosegger (1980: 198) showed that the estimated time interval between invention and major innovation is about 50 years: *e.g.* electric motor is about 58 years, electric arc lights 50 years,

[12] *cf.* also Lipsey *et al.*, 2005; Bresnahan, 2010; Ristuccia & Solomou, 2014; Goldfarb, 2005.

telegraph about 44 years, synthetic resins 52 years, etc. Overall, then, GPTs are a complex technology that induce and affect other technological innovations/products and/or construct a long-run platform in communications and energy systems for corporate, industrial, economic and social change over time (Coccia, 2015). Electricity power, information and communications technology are regarded as the prototypic General Purpose Technologies (Jovanovic & Rousseau, 2005).

## Study design and methodology

*Firstly*, to develop a theoretical framework for the technological analysis and representation of the evolution of GPTs over the long run,this study describes complex drivers of GPTs with a general overview of the socio-economic literature. *Secondly*, this study systematizes the *plexus* (interwoven combination) of drivers of GPTs by using a fishbone diagram, which can provide an appropriate visual representation of determinants underlying source and evolution of GPTs. Fishbone diagrams (also called Ishikawa diagrams or cause-and-effect diagrams) is a graphical technique to show the several causes of a specific event or phenomenon (fig. 1). In particular, a fishbone diagram (the shape is similar to a fish skeleton) is a common tool used for a cause and effect analysis to identify a complex interplay of causes for a specific problem or event. This causal diagram was created by Ishikawa (1990) in the research field of management.

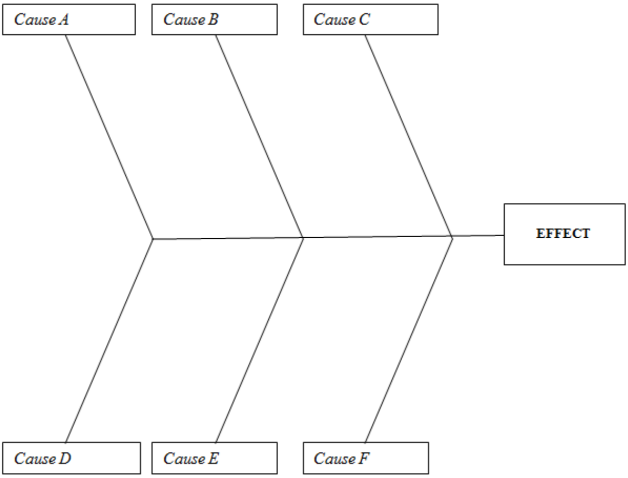


**Figure 1.** *A Fishbone Diagram*

As a matter of fact, this Cause and Effect Analysis was originally developed as a quality control tool, such as product design and quality defect prevention, to identify potential factors causing an overall effect. Each cause is a source of variation of the phenomena understudy. Causes are usually grouped into major categories to identify the overall sources of variation that lead to a main effect (Fig. 1). In general, the Fishbone diagram can be used as an appropriate visual representation of phenomena that involve the investigation of multiple cause-and-effect factors and how they inter-relate (*cf.* Ayverdia *et al.,* 2014; Buyukdamgaci, 2003; Ishii & Lee, 1996). Ramakrishna & Brightman (1986) compared their own Fact-Net-Model with Fishbone Diagram, and Kepner and Tregoe Method to show perceived differences. Overall, then, it seems that fishbone diagram can be an appropriate tool to represent the inter-related drivers of complex technologies, such as GPTs.

## A general description of the plexus of determinants generating major innovations

The source and evolution of major innovations (*e.g.* GPTs) depend on complex drivers. Economic literature shows several determinants of GPTs (*cf.* Ruttan, 2006; Bresnahan & Trajtenberg, 1995; Coccia, 2010; 2014; 2014a; 2015; De Marchi, 2016; Scientometrics, 1984). Some of them are discussed as follows.

### Relevant problem

GPTs are naturally directed to solve critical problems to achieve competitive advantages of leading nations (Coccia, 2015) or organizations in certain environments (Atuahene-Gima & Wei, 2011). Usher (1954) explained the evolution of new technology by using the theoretical framework of the Gestalt psychology. Usher's theory of cumulative synthesis is based on four concepts (*see* Basalla, 1988: 23): 1) Perception of the problem: an incomplete pattern in need of resolution is recognized; 2) Setting stage: assimilation of data related to the problem; 3) Act of insight: a mental act finds a solution to the problem; 4) Critical revision: overall exploration and revision of the problem and improvements by means of new acts of insight. This theory focuses on acts of insight that are basic to solve problems and generate vital innovations. The main implications of Usher's theory are the psychological aspects of invention and the evolution of new technology with a vital cumulative change (Basalla, 1988: 24). Coccia (2016) also shows, through an inductive study in medicine, that consequential problems support the evolution of several radical innovations, such as new and path-breaking technological trajectories of target therapy in oncology (*cf.,* Coccia & Wang, 2015).

## Geographical factors and temperate climate

Technological innovation is a vital human activity that interacts with geographic factors and natural environment. Geographical characteristics of certain areas support concentration and location of innovative activities and are also determinants of vital technological innovations (Krugman, 1991). The new geography of innovation analyses several spatial factors relating to the origin and diffusion of technological innovation, *e.g.,* spatial proximity and agglomeration (Rosenberg, 1992; Smithers & Blay-Palmer, 2001; Howells & Bessant, 2012). In particular, new economic geography argues that "*all* production depends on and is grounded in the natural environment" (Hudson, 2001: 300). Feldman & Kogler (2010) claim that the natural advantages of resource endowments and climate in certain places can induce innovationand economic growth (*cf.,* Moseley *et al.,* 2014). Lichtenberg (1960) shows that geographical factors, rather than proximity to raw materials or markets, influence the production of knowledge and the cumulative nature of several innovations. Audretsch & Feldman (1996) confirm that the agglomeration of innovative activities and firms is related to advantages in the natural environment, such as available resources and other factors of the physical geography. In general, the concentration of human and natural resources is in specific geographical places, such as major cities, long known to be society's predominant engines of innovation and growth (Bettencourt *et al.*, 2007). The climate is also a main geographical factor that affects natural resources, natural environment and human activities, such as the technical change. Long ago, Montesquieu (1947[1748]) argued that the climate shapes human attitude, culture and knowledge in society. Recent economic literature shows that warm temperate climates have an appropriate natural environment for humans that, by an evolutionary process of adaptation and learning, create complex societies, efficient institutions and communications systems. This socio-economic platform supports, in temperate latitude, the efficient use of human capital and assets that induce inventions, innovations and their diffusion over time and space (Coccia, 2015a).

## Cultural and religious factors

Barro & McCleary (2003: 760) argue that: "successful explanations of economic performance must go beyond narrow measures of economic variables to encompass political and social forces".In fact, modern literature is also analyzing social forces of economic development such as the culture (*e.g.* Guiso *et al.,* 2006: 23; Maridal, 2013). Weber (1956) discussed how the Protestant religious culture has affected the economic attitude of people and the entrepreneurship of capitalistic systems. Current socio-economic research also analyses the religion and culture as basic drivers of economic growth and innovation (*cf.* Barro & McCleary, 2003; 2005; Guiso *et al.*, 2006; Spolaore & Wacziarg, 2013; Coccia, 2014). Guiso *et al.* (2003) show the interplay between intensity of religious beliefs and people's attitudes that are conducive to economic growth (*e.g.,* cooperation, trust, thriftiness, government, institutions, women's propensity to work, legal rules, and fairness of the market). In particular, Guiso *et al.* (2003: 225): "find that on average, religious beliefs are… conducive to higher per capita income and growth… Christian religions are more positively associated with attitudes conducive to economic growth" (*cf.* Bettendorf & Dijkgraaf, 2010). Religion shapes people's attitude of mind, education, culture and institutions of countries and likely is also a main socio-cultural determinant of the patterns of technological innovation (Coccia, 2014). A study displays that, on average, societies with a predominance of the Protestant, Jewish and Eastern religions have technological performance higher than societies with other predominant religious cultures. These results may be due to fruitful relation between religion and higher education institutions of countries that support high human capital. In addition, a higher religious fractionalization in advanced society, *ceteris paribus*, has a positive effect on technological outputs. This appears to be particularly true among richer and more democratic countries, which are mainly located in the European and North-American geo-economic areas (Coccia, 2014). However, these findings are tentative and there is need for much more detailed research into the relations between religion, culture and innovation patterns.

## Population and demography

Population growth plays a main role for patterns of technological innovation. Kuznets (1960) claims that: "high population spurs technological change because it increases the number of potential inventors" (as quoted by Kremer, 1993). In particular, Kuznets (1960: 328) states: "Population growth… produces an absolutely larger number of geniuses, talented men, and generally gifted contributors to new knowledge whose native ability would be permitted to mature to effective levels when they join the labor force".Moreover, Kuznets (1960) and Simon (1977) argue that high populations have a higher probability to create potential inventors because larger populations have proportionally more individuals with new ideas. In fact, Jones states that: "'More people means more Isaac Newtons and therefore more ideas'" (as quoted by Strulik, 2005: 130). Moreover, many inventions and innovations are demand-driven by larger population, and an active demographic change and high population can play a vital role for supporting patterns of technological innovation in advanced national systems of innovation (Boserup, 1981: 5; Coccia, 2014a). Some studies also show that an optimal level of technological performance in advanced nations is due to positive growth rates of population but lower than 1% (percentage of annual population growth rates, Coccia, 2014a). This result confirms the study by Strulik (2005: 129) that: "long-run growth is compatible with a stable population".

### Major wars and environmental threats

Ruttan (2006) argues that the war may be one of contributing factors that generates GPTs. In general, the high mobilization of scientific, technical, and financial resources during major conflicts might support GPTs. In particular, a major war, or threat of a major war, may be a vital condition to induce political and economic institutions of great powers to commit the huge resources necessary to generate and/or sustain the development of new path-breaking technologies directed to provide a competitive advantage in aversive environments (Ruttan, 2006). Hence, Ruttan (2006: 184) argues that a *war* and/or *a threat of a majorwar* can support the development of strategic GPTs that subsequently generate clusters of commercial innovations for the economic progress in society.

### Purpose of global leadership

Coccia (2015) shows that the source of strategic GPTs is, *de facto*, due to purposeful systems (*e.g.* leading countries), with high economic potential and purposeful institutions having the purpose of achieving/sustaining a global leadership that can engender GPTs to cope with consequential environmental threats and/or to take advantage of important environmental opportunities. Coccia's (2015) theory generalizes the Ruttan's approach, developing the theoretical framework of global leadership-driven innovation: GPTs are originated by the purpose of the global leadership of great powers, rather than wars *per se*.

In short, this theory by Coccia (2015) stresses the thesis that the source of GPTs is due to the purpose of global leadership of great powers which generates a main impetus for solving relevant and strategic problems during military and political tensions, such as during the struggle to prove scientific and technological superiority, and military strength in space between U.S. and Soviet Union in the 1960s. This struggle for global leadership has generated major advances in ICTs and satellite technology, which are main GPTs in society. Another main example is given by U.S. Navy's Mobile User Objective System, a current GPT to support U.S. global leadership and, as a consequence, human progress (Coccia, 2016a).

## Democratization

Democracy can be seen as a set of practices and principles that institutionalize and protect freedom (Modelski & Perry, 2002; Norris, 2008). Barro (1999: 160) points out that "increases in various measures of the standard of living forecast a gradual rise in democracy". Acemouglu *et al.,* (2008) analyze the relationship between income per capita and democracy and argue that political and economic development paths are interwoven. Coccia (2010) shows that democratization is an antecedent process (cause) to technological and economic change by historical and statistical analyses. In particular, democratization seems to be a main driving force for technological change: most free countries, measured with liberal, participatory, and constitutional democracy indices, have a level of technological outputs higher than less free and more autocratic countries. As a matter of fact, it seems that "democracy richness" generates a higher circulation of information and appropriate higher education systems that, in advanced countries, support high human capital for fruitful patterns of technological innovation with fruitful effects for the wellbeing and wealth over the long run (Coccia, 2010).

## Research policy and national system of innovation

Governments in advanced economies devote much policy attention to enhancing investment in R&D to support the technical progress. In fact, R&D plays a key role for supporting both technical innovation and economic growth of modern economies, and includes expenditures by the industry, government, higher education and private non-profit sectors (*cf.* Jones & Williams, 1998: 1133*ff*; Coccia, 2012).

Griffith *et al.,* (2004) display that R&D has a direct effect on the growth of the Total Factor Productivity (TFP) across several

OECD countries. Instead, Mamuneas & Nadiri (1996, p.57) claim that: 'The optimal mix of… [incremental R&D tax credit and immediate deductibility provision of R&D expenditures] is an important element for sustaining a balanced growth in output and productivity in the manufacturing sector''. Zachariadis (2004) investigates the relationship between TFP and R&D investment and finds a positive relation between these variables (*cf.* Goel *et al.*, 2008). Instead, Coccia (2012) shows that when R&D spending of business enterprise sector exceeds R&D spending of government sector, the labor productivity and GDP tend to growth, *ceteris paribus*. Moreover, a range of R&D investment as percentage of GDP between 2.3 per cent and 2.6 per cent seems to maximize the long-run impact on productivity growth of advanced countries (Coccia, 2009). This finding is the key to explain the political economy of R&D for sustained productivity, accumulation of scientific and technical knowledge, as well as of technology improvements that are becoming more and more necessary to modern economic growth of nations over time.

## A comprehensive theoretical framework to represent the drivers of GPTs: the Fishbone diagram

This study suggests a comprehensive theoretical framework to represent and analyze the drivers of GPTs that explain the social and economic change over time. In particular, an appropriate visual representation of the complex drivers of major innovations can be the fishbone diagram. Figure 2 shows this comprehensive theoretical framework (Fishbone diagram) to explain the source and evolution of GPTs over time.

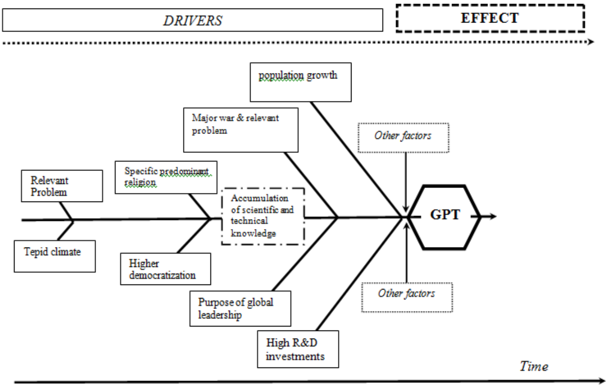


**Figure 2.** *Determinants of the source and evolution of GPTs in advanced nations represented with the fishbone diagram.*
**Note:** GPT = General Purpose Technology

In particular, the fishbone diagram in Figure 2 shows that the source of GPTs is due to a complex interplay of causes represented at left, which support the evolution of GPTs (hexagon at right). Firstly, the presence of relevant problems in temperate climate for advanced countries with socioeconomic potential is the first stage for laying the foundations for a GPT. This condition is a necessary, but not a sufficient factor because the GPTs need specific socioeconomic and cultural background represented by high level of democratization and specific predominant religions, such as Protestant religion that can fruitful affect the higher education system and culture of human resources in society. However, an appropriate socioeconomic background is an important base for the source of major innovations but GPTs thrive mainly when great powers have to achieve and/or support the purpose of global leadership to cope with consequential environmental threats and/or take advantage of important opportunities (*e.g.,* during major conflicts/threats and/or struggle to prove scientific superiority and military strength). These factors are supported by an efficient and strong national system of innovation that invests high economic and human resources to solve relevant problems by creating new technology and, as a consequence, strategic competitive advantages for sustaining patterns of economic growth. In this context, high growth rates of population also play a vital role to support the evolution of leading societies and long-term development of GPT and major technologies.

The sequential and complex factors, represented in Figure 2, are basic for the source of GPTs that support long-run human development in society.

A final and important implication of this theoretical framework is that some of the features and determinants that cause GPTs seem to be enduring and invariant properties of human societies, rather than accidental shocks/events (*cf. also* Wright, 2005). Hence, GPTs seem to have regularity in their historical developmental paths driven by specific environment in which great powers, with socioeconomic potential, endeavour to achieve and/or sustain the purpose of global leadership.

## Examples of fishbone diagrams in history of technology

The source of some GPTs visualized with the Fishbone diagram is represented as follows.

Drivers of Steam Engine in England

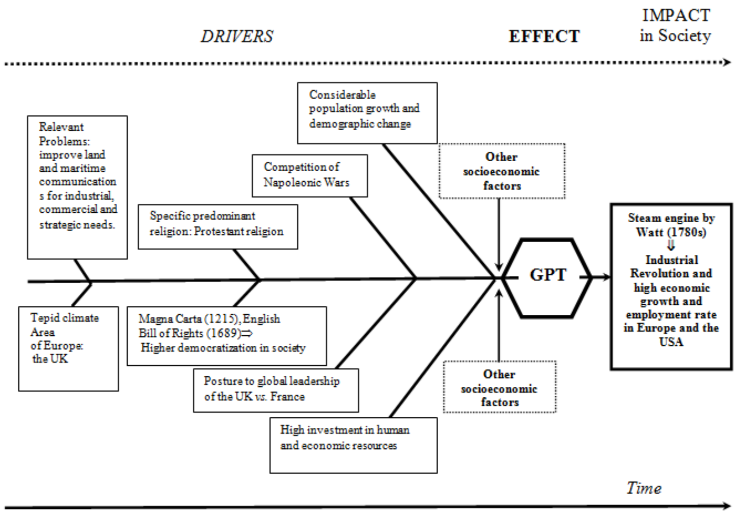


**Figure 3.** *Determinants of the source of Steam engine from 1700s with the fishbone diagram*

The sources of the GPT of Information and Communications Technologies (ICTs) in the U.S. A.

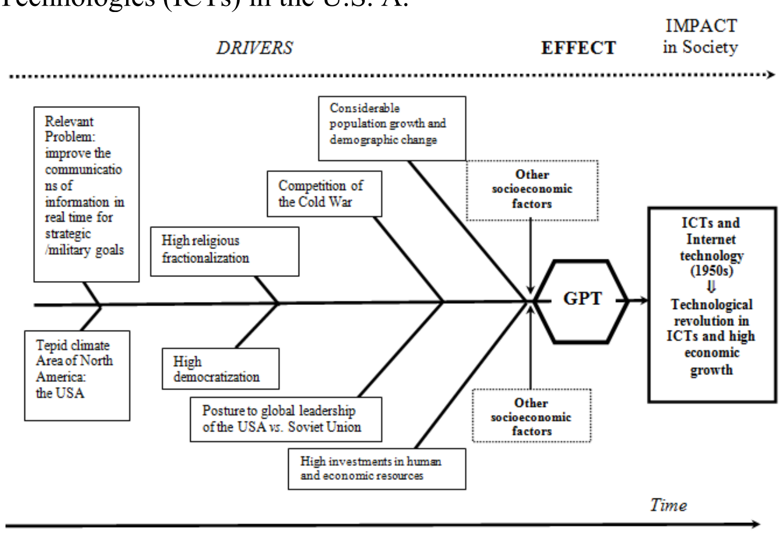


**Figure 4.** *Determinants of the source of ICTs from 1950s represented with fishbone diagram*

# Conclusions

History of technology shows that GPTs create strategic platforms for several products/processes such as in communications and transportation technology for lung-run human development (Singer *et al.,* 1956). In general, GPTs are driven by a large number of factors and it is important a simple visual representation for explaining their source and evolution over time. What can be learned from fishbone diagram designed here to represent the determinants of GPTs?

A main finding of this study is that the fishbone diagram offers an appropriate theoretical framework for a visual representation and technological analysis of complex factors of major innovations over time. This tool shows clearly and simply the sequential and inter-related determinants of the source and evolution of GPTs over time and space.

In particular,

(1) The conceptual framework here shows a visual representation of complex and inter-related factors driving GPTs with a cause-effect approach over the long run;

(2) The visual representation here is able to show similar drivers of several GPTs and to detect regularity of sources over time and space;

(3) The visual representation here is able to explain *how* and *why* GPTs thrive in specific geo-economic areas and time period.

The theoretical framework of this study satisfies main concepts of the philosophy of science, such as *consilience, simplicity and analogy* (Thagard, 1988, Chp. 5). In particular,

This conceptual framework seems to be consilient, since it explains a greater number of similar drivers for different GPTs in the history of technology.

The simple elements of the study here are well known in economic and managerial literature. The idea that GPTs is associated to different factors is not new, however, the idea that a fishbone diagram can provide an appropriate visual representation of sequential and inter-related drivers of GPTs has not been used in current literature to display and explain the complex source of major innovations.

The characteristic of *analogy* of results is well-established by using the Fishbone diagram for representing and explaining the source of different major technologies at micro- and macro-level of analysis. In short, the fishbone diagram seems to be a general tool for technological analyses of sources of GPTs and other new technologies.

The findings of this study also show that some determinants of new technology can be contest-dependent, whereas other ones can be invariant factors for the origin of GPTs over time and space. Future research on these topics, to reinforce this study, should (1) focus on additional and intervening factors affecting the source of GPTs; (2) measure the evolution of GPTs and derived technological trajectories by using phylogenetic approaches.

Overall, then, the study here seems to establish a general comprehensive theoretical framework for an appropriate visual representation and technological analysis (the fishbone diagram) of the complex drivers of major innovations over time (*e.g.*, GPTs). However, we know that other things are often not equal over time and place in the history of technology and therefore results here are tentative. In fact, Wright (1997: 1562) properly claims that: "In the world of technological change, bounded rationality is the rule". More fine-grained studies will be useful in future, ones that can more easily examine other complex predictors of emerging GPTs.

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# 7. Motivations of scientific research in society

## Introduction: What is science and scientific research?

The purpose of this study is to criticize the motivations of nations to do scientific research to explain and generalize properties over time and space. Before discussing these topics, the study here clarifies the concept of science and scientific research.

The term science has different meanings. Science is an accumulation of knowledge and includes basic and applied fieldsof research (Coccia & Wang, 2016; Godin, 2001). The Scottish philosopher Rae (1834, p.254) states that: "the aim of science may be said to be, to ascertain the manner in which things actually exist". A different definition of science was given by Crowther (1955): "Science is a system of behavior by which man acquires mastery of his environment". Volta (1792)[13] considered science in an experimental perspective that has its greatest and most rewarding moments in practical activity. As a matter of fact, science for Volta (1792) is invention and it is driven by scientists' aptitude and/or passion for the construction of new devices and artifacts. Bernal (1939, p.6) considered science "the means of obtaining practical mastery over nature through understanding it". Instead, Dampier (1953) claimed that science is: "Ordered knowledge of natural phenomena and the rational study of the

[13] Alessandro Volta (1745-1827) Italian physicist, known for his pioneering studies in electricity. He also invented the electric battery in 1800.

relations between the concepts in which those phenomena are expressed". Russell (1952) provided a broader definition of science: "Science, as its name implies, is primarily knowledge; by convention it is knowledge of a certain kind, namely, which seeks general laws connecting a number of particular facts. Gradually, however, the aspect of science as knowledge is being thrust into the background by the aspect of science as the power to manipulate nature". According to Freedman (1960) the definition by Russell (1952) is the more satisfactory, while Dampier's definition relates only to scientific knowledge, and does not take into account either the application of such knowledge, or the power to apply it towards control and change of man's environment. However, Russell (1952) describes science as static, whereas it is a dynamic process.

Kuhn (1962) states that:

> Science is a constellation of facts, theories, and methods… Hence scientific development is the fragmentary process through which these elements have been added, singularly or in groups, to the ever growing depository that constitutes technical and scientific knowledge.

Lakatos (1968, p. 168, original Italics and emphasis) argues that:

> Science… can be regarded as a huge research program… progressive and degenerating problem-shifts in series of successive theories. But in history of science we find a continuity which connects such series. …The programme consists of methodological rules: some tell us what paths of research to avoid (*negative heuristic*), and others what paths to pursue (*positive heuristic*) - By 'path of research' I mean an objective concept describing something in the Platonic 'third world' of ideas: a series of successive theories, each one 'eliminating 'its predecessors (in footnote 57) - … What I have primarily in mind is not science as a whole, but rather particular research-programmes, such as the one known as 'Cartesian metaphysics. ...a 'metaphysical' research-programme to look behind all phenomena (and theories) for explanations based on clockwork mechanisms (positive heuristic). A research-programme is successful if in the process it leads to a progressive problem-shift; unsuccessful if it leads to a degenerating problem-shift …Newton's gravitational theory was possibly the most successful research-programme ever (p. 169). …The reconstruction of scientific progress as proliferation of rival research-programmes and progressive and degenerative problem-shifts gives a picture of the scientific enterprise which is in many ways different from the picture provided by its reconstruction as a succession of bold theories and their dramatic overthrows (p. 182).

Considering these different perspectives, Freedman (1960, p. 3) suggests the following definition of science:

Science is a form of human activity through pursuit of which mankind acquires an increasingly fuller and more accurate knowledge and understanding of nature, past, present and future, and an increasing capacity to adapt itself to and to change its environment and to modify its own characteristics.

This study argues that:

Science discovers the root causes of phenomena to explain and predict them in a context of adaptation of life to new economic and social bases.

Table 1. Synthetizes some definitions of science and scientific research given by scholars

**Table 1.** *Scholars and suggested definition of science*

| *Authors (year)* | *Suggested definition of science and scientific research* |
|---|---|
| Volta (1792) | Science has its greatest and most rewarding moments in practical activity and is driven by scientists' aptitude for the construction of new devices and artefacts |
| Rae (1834) | The aim of science is to ascertain the manner in which things actually exist |
| Bernal (1939) | Science is the means of obtaining practical mastery over nature through understanding it |
| Crowther (1955) | Science is a system of behavior by which man acquires mastery of his environment |
| Dampier (1953) | Ordered knowledge of natural phenomena and the rational study of the relations between the concepts in which those phenomena are expressed |
| Russell (1952) | Science is primarily knowledge; by convention it is knowledge of a certain kind, namely, which seeks general laws connecting a number of particular facts. …the aspect of science as knowledge is being thrust into the background by the aspect of science as the power to manipulate nature |
| Freedman (1960) | Science is a form of human activity through pursuit of which mankind acquires an increasingly fuller and more accurate knowledge and understanding of nature, past, present and future, and an increasing capacity to adapt itself to and to change its environment and to modify its own characteristics. |
| Kuhn (1962) | Science is a constellation of facts, theories, and methods… Hence scientific development is the fragmentary process through which these elements have been added, singularly or in groups, to the ever growing depository that constitutes technical and scientific knowledge. |
| Lakatos (1968) | Science . . . can be regarded as a huge research program . . . .progressive and degenerating problem-shifts in series of successive theories. But in history of science we find a continuity which connects such series. . . . |
| Coccia (2018, this paper) | Science discovers the root causes of phenomena to explain and predict them in a context of adaptation of life to new economic and social bases. |

These different views of science show that the concept of science is elusive and a definition of science is a hard task because of the nature of science itself. In this background of social studies of science, it is possible to clarify the concepts of research and scientific research. Generally speaking, research is continued search for knowledge and understanding in society. Instead, scientific research is a continued search for advancing scientific knowledge, applying methods of inquiry.

This study considers scientific research as: scientific research is a systematic process, applying methods of scientific inquiry, to solve consequential problems, to satisfy human wants, to take advantage of important opportunities and/or to cope with environmental threats. In addition, scientific research, as a systematic process, is driven by an organized social effort of nations to make science advances and discoveries known to the rest of humankind.

The dual elements of the scientific nature of a research are: determination of problems and utilization of the methods of inquiry (they are organized and systematic scientific thinking used by scholars for controlled investigations and experiments to logically and efficiently solve theoretical and practical problems, and generate discoveries and/or science advances, see Coccia, 2018g).

In particular, scientific research can be carried out with following general methods of inquiry (Coccia, 2018g):

- *Inductive approach* starts from the experimental observation of phenomena and traces back the laws that regulate them by means of experiments, analogies, and hypotheses;
- *Deductive approach* starts from theory and general ideas in order to predict new laws and explain new phenomena.

The process of scientific research can be described with the theoretical framework of the Gestalt psychology given by (see Basalla, 1988, p.23; cf., Usher, 1954) Perception of the problem: an incomplete pattern in need of resolution is recognized; 2) Setting stage: data related to the problem is assembled; 3) Act of insight: a mental act finds a solution to the problem; 4) Critical revision: overall exploration and revision of the problem and improvements by means of new acts of insight.

Although several contributions in social studies of science, the problem of why nations sustain science and scientific research is hardly clarified. In particular, which complex factors drive nations to support science and scientific research are basic to explain human development in society (Coccia & Bellitto, 2018). In light of the continuing importance of these topics in the social studies of science, this paper seeks to explain critical factors supporting nations to produce science and scientific research in society.

## Why do nations produce scientific research in society?

Scientific research reflects the social climate in which it is carried out. Most of the significant discoveries are a systematic, generally organized process of scientific research that reflects the outward-looking tendencies in society. Bernal (1939) analyzed the social function of science considering its practical activities as the basis of progress. Bernal (1939) also argued that science is produced for social and economic interests of nations rather than a philosophical inquiry. A main implication is that the immense growth of science in modern society is not only due to activity of scientists but rather to general social efforts of nations to take advantage of important opportunities and/or to cope with environmental threats, such as war. In general, scientific research has been less a matter of individual enterprise and more an organized social effort (Coccia & Wang, 2016). Social climate of nations affects the development of scientific research, the understanding and appreciation of scientific discoveries in society. Scientists inevitably reflect the concerns and interests of their home society. Figure 1 shows some factors affecting the production of scientific research by nations and next sections endeavor to explain these factors.

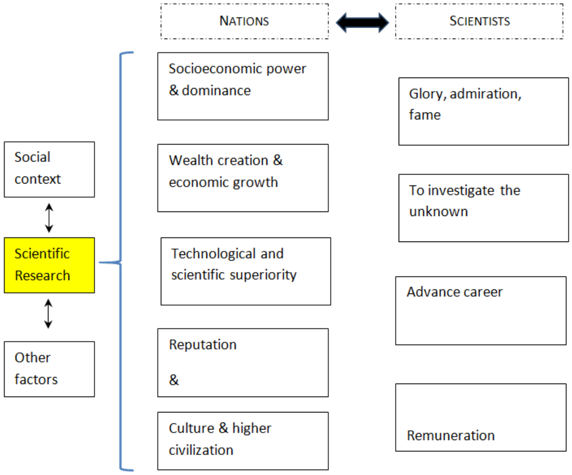


**Figure 1.** *Factors associated with the production of scientific research by nations and scientists*

## Scientific research as a source of socioeconomic power

A nation can perform scientific research to support a socioeconomic power directed to take advantage of important opportunities and/or to cope with consequential environmental threats, such as war. Socioeconomic power of a nation is based on a process of influence on other subjects towards the accomplishments of some goals (e.g., mutual trade), in some cases associated with(formal and/or informal) dominance and control of geoeconomic areas. Scientific research can generate achievements that are also important in the presence of socioeconomic shocks, such as warfare (cf., Ruttan, 2006; Constant, 2000; Mowery, 2010). The investigation of war economy and mainly of war consequences can help to understand the reasons why nations perform scientific research. A main purpose of societies in war is to take advantage of opportunities to have fruitful socioeconomic consequences and gain dominance and control on other areas. In the Ancient period, the victory in war was due to the strength and prowess of population, whereas the modern warfare depends more and more on scientific, technical and engineering knowledge of nations (Coccia, 2015; 2017). Current international conflicts are won in research labs with high-tech weapons and cyber power (cf., Kramer *et al.,* 2009). The pioneering studies by Neurath (1919) showed the stimulating effect of war on technical and scientific progress of countries. Recently, some social scientists have paid more attention to the effects of scientific research on technology during war and post war period (cf., Coccia, 2015, 2017, 2018; Ruttan, 2006; Mowery, 2010). War can support not only scientific research but also other types of novelties, such as innovative laws and regulations. Moreover, social scientists have a theoretical reluctance to differentiate between types of warfare. The tendency is to treat war as a generic phenomenon with equivalent socioeconomic impact, whereas some wars are more important than others in terms of impetus for nations to produce scientific research, discoveries and new technology. In particular, there is a distinctiveness of world war, which generates major socioeconomic consequences and many science advances by countries to gain dominance and global leadership (Stein & Russett, 1980, p.401; Coccia, 2015).

Nations support scientific research to have a high *economic potential* based on a scientific and technological superiority both in peacetime and in warfare period (cf., Mendershausen, 1943, p.8; Smith, 1985). Recent studies by Ruttan (2006) analyze the relation among war, science, innovation and economic growth of countries. Ruttan (2006, p.184*ff*) argues that without a *threat* of a major war, it is difficult that the U.S. political system mobilizes huge human and economic resources to support the development of major and strategic discoveries that subsequently can be translated in commercial innovations for the progress in society. In short, the fruitful factors at the origin of vital discoveries and science advances thrive in the presence of international conflicts and crises, driven by common institutional, entrepreneurial and scientific energies, to cope with consequential environmental threats. *Innovative spirit* guide scientific research of countries in the presence of war,based on two critical drivers: *demand factors* spur a huge demand shock because of a massive increase in deficit spending with expansionary policy (cf., Field, 2008); *supply factors*: learning by doing in military production, spin-off and spillover from military R&D, etc. Wright (1997, p.1565) examines the "American technological leadership" and shows that critical manufacturing sectors for U.S. economy[14] have taken advantages from fruitful demand- and supply-side effects of wars (cf. also, Goldfarb, 2005). The mobilization for wars increases R&D investments to produce sciences advances associated with military technologies that are transferred to civilian applications in the long term to support a higher economic potential and economic growth (Goldstein, 2003; Stein & Russett, 1980, p.412). In particular, a strong economic and scientific potential has a vital role to win wars for the distribution of power within the international system (Modelski, 1972; cf., Levy, 2011). Modelski (1972, p.48) asserts that the "war causes the Great Powers", which affect the political and economic system worldwide (e.g., Roman Empire over 200BC ~ 400AD, Britain Empire in the 1710-1850 period, the USA from 1940s onwards, etc.; cf., Stein & Russett, 1980). In fact, Ferguson (2010) claims that the United States has a global leadership because of a stronger military, political, scientific, technological and economic potential worldwide recognized.

Instead, Coccia (2015, 2017) suggests that sources of science and technology are, *de facto*, associated with the goal of global leadership of purposeful systems (e.g., nations) in the presence of effective and/or potential environmental threats, rather than warfare *per se*. In short, the source of major science advances seems to be driven by solution of relevant and strategic problems - in the presence of consequential environmental threats to national security-, in order to achieve/sustain/defend the position of global leadership by nations.

[14] For instance: aircraft, electrical machinery, non-electrical machinery, chemicals and allied products, and motor vehicles.

Table 2 shows that nations, such as the USA having higher investments in R&D, generate higher innovative outputs and GDP per capita than other nations: these factors are proxies of socioeconomic power. Moreover, Coccia (2015, 2017) shows that U.S. Department of Defense had about 700 foreign installations in 2000s in more than 60 countries worldwide (U.S. DoD, 2003, 2012). The high presence of U.S. military installations confirms the U.S. global leadership, achieved winning World War II, associated with a high economic, scientific and technological potential worldwide recognized (Coccia, 2015). As a matter of fact, nations invest in scientific research to support new technology to be more efficient in the presence of effective and/or potential international conflicts, environment threats and across markets; for instance, military and political tensions between U.S. and Soviet Union in the 1960s, during the period of Cold war, have supported a high investment in scientific research that has generated many discoveries and new technology in order to prove scientific and technological superiority worldwide, and military strength in space (cf., Kira & Mowery, 2007; Ruttan, 2006).

**Table 2.** *R&D investments and innovative output of leading nations to support socioeconomic power worldwide*

| Countries | Average Military expenditure by country as percentage of gross domestic product 1992-2013* | Average Research and Development expenditure (% of GDP) 1996-2005ϕ | Average Patent applications, residents per million People 1985-2005ϕ | Average GDP per capita, PPP (constant 2005 international $) 1989-2006ϕ |
|---|---|---|---|---|
| United States | 3.90 | 2.66 | 447.20 | 36,318.11 |
| Russia/USSR | 3.87 | 1.09 | 145.84 | 9828.36 |
| France | 2.64 | 2.18 | 224.04 | 27,439.67 |
| UK | 2.60 | 1.82 | 334.51 | 26,565.94 |
| China P. R. | 1.99 | 0.92 | 18.00 | 2,398.01 |

**Note:** * SIPRI Military Expenditure Database (2012); ϕ World Bank (2008).

## 2.2. Scientific research as a source of economic growth and competitive advantage of nations

Bacon (1629) [15] believed that science had the power to improve the society's economy and standard of living. In his work *New Atlantis* (Bacon, 1629), he saw science, technology, politics, industry, and religion as deeply intertwined. Stephan (1996, p. 1199) argues that science is one of the sources of economic growth. In particular, science supports technological innovations

[15] Bacon is known as the father of the English empiricist philosophy, a tradition that includes Locke, Hume, J.S. Mill, Russel.

and has interrelationships with economic growth and other socioeconomic forces (Coccia, 2017, 2018).

The endogenous growth theory is one of the most prominent developments in the field of economic theory (Nelson & Romer, 1996). Romer (1994) and Lucas (1988) argue that economic growth depends on – i.e.,it is endogenous to – investments in scientific research and education. The endogenous growth theory is influencing modern economic policies of both industrialized and emerging countries, since investments in higher education, as well as in R&D of firms and public research organizations are vital elements for the increase ofnew technology, productivity and economic growth within national innovation systems (Coccia, 2004, 2005h, 2011, 2013, 2013a, 2016; Coccia *et al.,* 2015; Coccia & Cadario, 2014; Coccia & Rolfo, 2002, 2009, 2010, 2013; Larédo & Mustar, 2004). However, Bernal (1939), writing between the two World Wars, was not optimistic about science. Barnal's work explicitly recognizes the lack of direct links between social and scientific progress. In fact, science advances, associated with technological progress, can also generate negative effects, such as a higher pollution and incidence of cancer in society (Coccia & Bellitto, 2018). Coccia (2015b) seems to reveal a main interrelationship between high scientific, technological and economic performance (indicators of human progress) and high diffusion of some cancers between countries, controlling screening technology (e.g., computed tomography).

## Scientific research as a source of new technology

One of the reasons to invest in R&D is to generate new technology that, in turn, supports competitive advantage of firms and nations (Porter, 1985; 1990). This argument can be explained with the linear model by Bush (1945):

*basic physics→large scale development→applications→military and civil innovations* (1)

Linear model of R&D [1] considers a stepwise progression from basic science, discoveries through applied research to technological development in firms and research labs, leading to a cluster of new products for wellbeing in society. Rothwell (1994, p.40, original emphasis) argues that the underlying reason that leads nations to invest in scientific research is that "more R&D in 'equalled' more innovation out". The model [1] is improved over time with a more general process of coupling between science, technology and market, as well as systems integration and networking within and between public and private R&D

laboratories directed to produce scientific research and new technology, which are beneficial for society and its wellbeing. Bush (1945) also suggests that basic science should be publicly funded and left to itself in order to produce advances in applied science and technology. This perspective was influential on the post-war research policy in a period of accelerated economic growth (Bush, 1945). Callon (1994) argues that public subsidy to support emerging research fields is needed, though results can be uncertain and/or achieved only in the long run, such as in gravitational astronomy that studies the sources of the universe. De Solla Price (1965) recognizes the interaction between science and technology and uses the metaphor of two dancing partners who are independent but move together (cf., de Solla Price, 1963; Kitcher, 2001). Finally, Gibbons & Johnston (1974) argue that scientific research of nations generates value that can be applied to solve specific problems, translating the results of scientific research in industrial environment for increasing employment and wealth of nations.

## Scientific research to increase reputation and recognition within and between scientific communities and nations

Stephan & Levin (1992) and Stephan & Everhart (1998) argue that scientists in their social context are interested in three types of rewards:

1) the game, the satisfaction derived from solving a problem and investigating the unknown. Hull (1988, p.305) describes scientists as being innately curious to investigate the unknown to achieve glory, fame and recognition. However, the activity of scientists, research teams, universities and research labs reflect an organized social effort of nations in specific historical periods (Stephan, 1996).

2) the glory and fame: the prestige that accompanies priority by scientists and nations in discovery. Merton (1957, 1968, 1972) argues that the goal of scientists and nations is also to establish priority of discovery by being first to communicate an advance in science worldwide. Publication is a lesser form of recognition, but a necessary step in establishing priority knowledge and that the rewards to priority are the recognition awarded by the scientific community and other nations for being first (Stephan, 1996). Dasgupta & Maskin (1987) argue that there is no value added when the same discovery is made a second, third, or fourth time. To put sharply, the winning research unit is the sole contributor to social surplus. Zuckerman (1992) estimates that, in the early 1990s, around 3,000 scientific prizes were available in North America

alone to support recognition of scholars and research labs. A defining characteristic of winner-take-all contests is inequality in the allocation of rewards. In fact, scientific research generates extreme inequality with regard to scientific productivity and awarding priority. This feature also generates the high productivity of some researchers and universities (e.g., MIT, Harvard University, Yale University, etc.) based on cumulative learning processes, called Matthew effect in science (Merton, 1957). This effect shows that researchers/research labs/universities who accomplish prominent results at the beginning of their history have an initial advantage over others and increased chances of obtaining further financial support as well as of accomplishing further discoveries.

3) the monetary rewards. Financial remuneration is another component of the reward structure of science. Compensation in science is generally composed of two parts: one portion is paid regardless of the individual's success in races, the other is priority-based and reflects the value of the winner's contribution to science. While this clearly oversimplifies the compensation structure, the role played by counts of publications and citations in determining raises and promotions at universities is evident from the work by Diamond (1986). Moreover, discoveries and science advances generate patents that are a main source of money that leads to new technology supporting employment and competitiveness of nations worldwide (Jaffe & Trajtenberg, 2002).

## Scientific research as a source of profit and socioeconomic problems of marketization in science

The connection between science and industry supports economic growth and progress (Coccia, 2012b). Rosenberg (1974) argues that science produces advances in scientific knowledge that can reduce the cost of solving complex technological problems and the cost of producing new technology. Mansfield (1995) shows that scientific research has a main impact on innovative products and processes in industry (cf., Jaffe & Trajtenberg, 2002). He also shows that some high-tech sectors have fruitful interactions between technology and basic sciences. Moreover, many nations support a growing commercialization of scientific research and technology transfer to support profit of firms (Slaughter & Leslie 1997; Coccia, 2004, 2009b). The commercialization of scientific research for maximization of profits by firms is driven by efficient R&D labs (Coccia, 2016a). For instance, leading firms in biopharmaceutical sectors invest in Research and Development (R&D) a high level of economic and human resources to support new knowledge and drug discovery to maximize the profit with new compounds (Coccia, 2014f, 2015c, 2018f), such as:

- AstraZeneca (UK-Sweden) invested about US$ 4 billion in 2012
- Roche (Switzerland) about US$ 10.6 billion US
- Boehringer Ingelheim (Germany) about $ 4.3 billion euro of R&D investments

In current competitive markets, public research labs have also a market orientation with many characteristics of business firm (cf., Coccia, 2012e). However, this phenomenon has been criticized because "the embracement of the market is compromising scientific norms and commercialization (or commodification, or marketization) is in profound conflict with the function and main mission of research units and universities" (Musselin, 2007; cf. also Greenfeld, 2001), that is, knowledge creation through research and dissemination through publication and education (Schuetze, 2007; Slaughter & Leslie, 1997). Washburn (2005) offers a highly critical assessment of close science and industry ties for profit maximization, showing "the great and dangerous influences that money and corporate ties impose." The "massification" of scientific research, associated with business and commercial interests, is influencing science in an "unsavory manner." Nelson (2005) states that "there are real dangers that unless [marketization of the scientific research] is halted soon, important portions of future scientific knowledge will be private property and fall outside the public domain [and] that could be bad news for future progress of science and for technological progress." The risk of this tendency, according to Laudel (2006), is that basic research and knowledge might suffer. Certain lines of basic research, whose success is difficult to predict, might become "endangered species" (Laudel 2006). Such forebodings are relevant to modern, knowledge-driven economies in their support R&D management to foster academic institutions and labs that play a driving role as "engines of growth," based on their intangible capital, brainpower. In this context, Rosenberg & Birdzell (1990) argue that science pushes the frontiers of knowledge creating economic resources for firms and nations. However, science advances can also increase the economic gap between countries that apply a Western-style of production and others not applying it.

## Public and private scientific research for supporting productivity of nations

Scientific research and innovation take up considerable economic and human resources that contribute to the accumulation of intangible capital of countries for long-term economic growth (Lucas, 1988; Romer, 1994; Porter, 1985, 1990). R&D investments are a main indicator of the level of science and scientific research of nations (Coccia, 2008a, 2012b). Several studies confirm the positive influence of Research & Development (R&D) expenditure on the growth of productivity of nations (Mairesse & Sassenou, 1991; Amendola *et al.,* 1993; Hall & Mairesse, 1995; OECD, 2003). Many studies aim at understanding whether public investment in R&D is a complement or substitute for R&D private investment (Blank & Stigler, 1957; Kealey, 1996; Coccia, 2010b, 2010e) but, despite the vast scientific literature, results are rather ambiguous. Some studies show that public financing has spillover effects on private investments in R&D (Adams, 1990; Jaffe, 1989; Toole, 1999). In particular, Grossman & Helpman (1991) show that spillovers from R&D are an important source of growth. Other studies show how public and private R&D investments influence the productivity of countries (Levy & Terleckyj, 1983). Lichtenberg & Siegel (1991) and Hall & Mairesse (1995) provide indications of the correlation between R&D investment and productivity. Amendola *et al.,* (1993) present well-documented evidence that R&D investment has noticeable effects on the growth of both productivity and competitiveness of nations. According to Brécard *et al.,* (2006), R&D produces effects on aggregate productivity gains. Griffith *et al.,* (2004) claim that R&D has a direct effect on the growth of Total Factor Productivity (TFP) in a panel of sectors for 12 OECD countries. Aghion & Howitt (1998) claim that R&D investment causes productivity growth, which in turnsupports the Gross Domestic Product (GDP). Zachariadis (2004) uses aggregate data from manufacturing sector for a group of OECD countries in 1971-1995 and he finds that R&D intensity has a positive impact on growth rates of both productivity and GDP. Zachariadis (2004), Guellec & van Pottelsberghe de la Potterie (2004) also show the positive relationship between TFP and R&D investments. About the relation between public and private R&D investments, Wallesten (1999) gives evidence for a crowding-out effect, whereas Robson (1993) claims that there is one-to-one complementarity. Blank & Stigler (1957) use a sample of firms to show that there is a substitution effect, but by changing the sample they find a complementarity effect. David *et al.,* (2000) argue that 1/3 of the case studies at firm, sector, and aggregate levels show a substitution effect of public research expenditure for private investments.

A complete analysis of the substitution or crowding out effect of R&D expenditure is necessarily related to the understanding of the decision mechanisms used by public bodies (governments and departments) and private subjects (e.g., firms). Coccia (2010b, 2010e) shows that at the aggregate level, the complementarity between public and private R&D investment but it is important for the government to support a level of public R&D expenditure, as part of the total GDP, lower than that of business R&D investment in order to drive productivity and economic growth in the long run. Therefore, in order to produce positive effects at national level, public R&D expenditure should be lower than the firms' expenditure to avoid crowding out effects. Moreover, high public R&D financing can be counterproductive and increase public deficit, with negative repercussions on interest rates and country's future economic performances (cf., Coccia, 2017i). Steil *et al.*, (2002) claim that in the USA, Japan, Germany, France, and the UK, the interventionist role of the government in the economic field has reduced in favor of that of the market forces, which have become more important in the allocation of resources within the research sector, even though several governments have not yet solved problems regarding under-investments in basic research, which is a public good (Arrow, 1962). In 2002, the European Unioninduced European countries, in line with international trends, towards an increase in R&D investments: the goal was 3% of the GDP, 56% of which should be financed by the private sector, in order to achieve the innovation intensity and growth levels of the USA by 2010 (European Commission, 2003; 2004; 2005; Room, 2005). This result could have been achieved if governments had implemented a range of incentives to private firms to stimulate their industrial R&D investments. In particular, governments should encourage industrial research labs of firms to recruit scientists and engineers from universities and public labs, so that the economic system has more industrial scientists and fewer academic scientists. In 2018, the ambitious target of 3% of R&D/GDP within EU countries is fail due to economic turmoil in 2000s and socioeconomic problems of high public debt within many countries (Coccia, 2017i).

Coccia (2010b, 2010e) confirms high economic performances in countries with low public financing to R&D associated with high investments in research by private enterprises (e.g., in the UK, the USA, Germany, etc.). Private firms are capable of investing in a much better way than the Government, the politicians, and the bureaucrats do for increasing employment, economic growth and wealth of nations (Coccia, 2010e). Figures 2-4 show low economic performances in countries (for example Italy) whose public expenditure in R&D is higher than private expenditure. In brief, the public policy of stimulating private investments in research rather than public R&D investments, it increases labor productivity per hour worked and long-term economic growth. Theeffects of these research policies are amplified when combined with economic stability, effective regulations, liberalizations, and competition policies.

Coccia (2009a) also shows that the range of gross domestic expenditure on R&D expressed as percentage of GDP (GERD) between 2.3 per cent and 2.6 per cent maximizes the long-run impact on productivity growth and it is the key to sustained productivity and technology improvements that are becoming more and more necessary to modern economic growth. Moreover, Coccia (2018f), based on OECD data, reveals that (very) high rates of R&D intensity and tax on corporate profits do not maximize the labor productivity of nations. In particular, the models suggest that the R&D intensity equal to about 2.5% and tax on corporate profits equal to 3.1% of the GDP seem to maximize the labor productivity of OECD countries (Fig. 5 and 6).

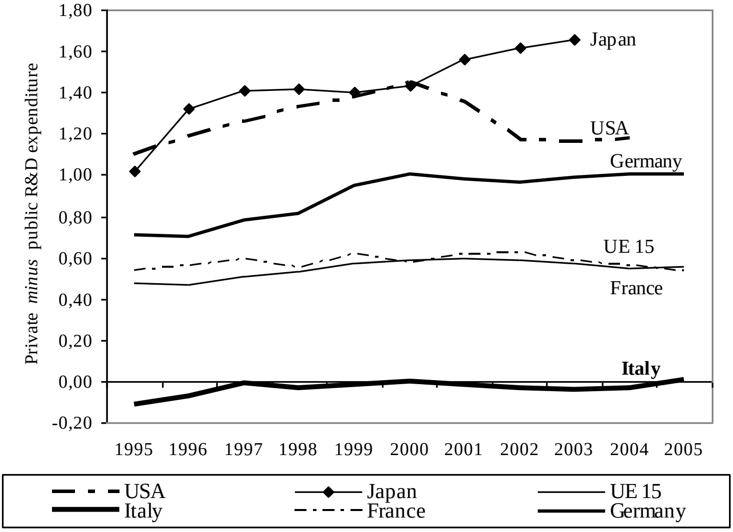


**Figure 2.** *Private minus public R&D expenditure over time per country.*
*Source: Coccia, 2010b; 2010e*

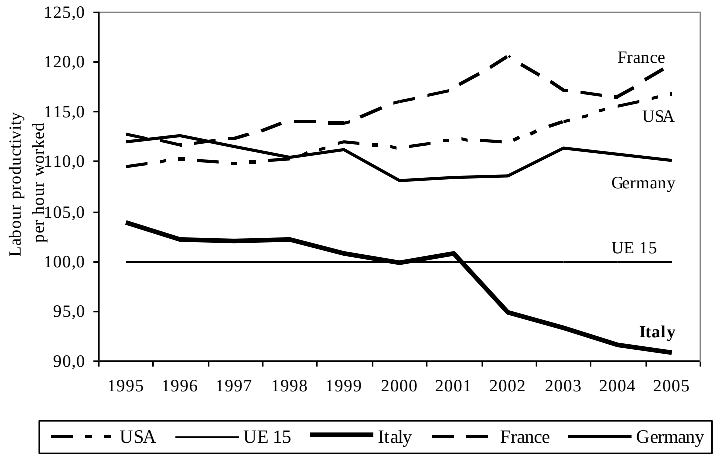


**Figure 3.** *Labor productivity per hour worked over time per country. Source: Coccia, 2010b; 2010e*

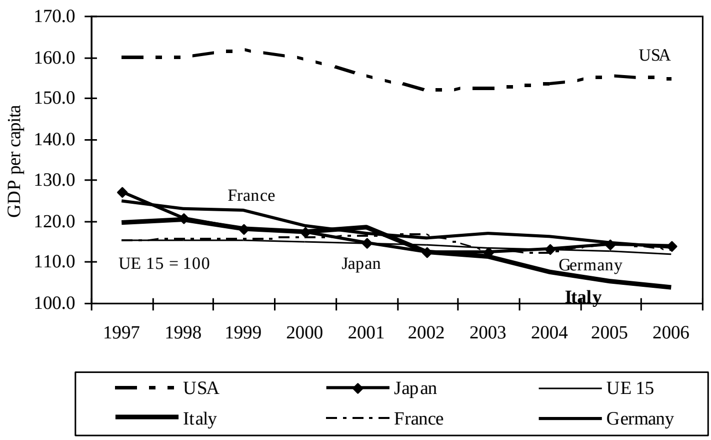


**Figure 4.** *Trend of GDP per capita over time per country.* ***Source:*** *Coccia, 2010b; 2010e*

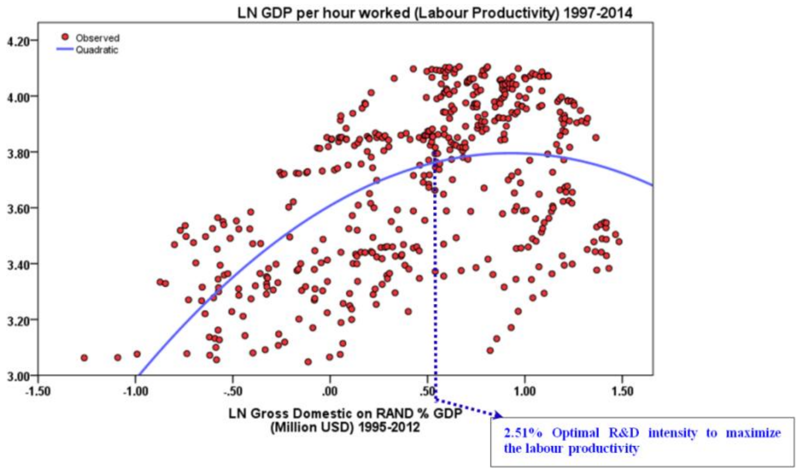


**Figure 5.** *LN GDP per hour worker (Labour productivity) 1997-2014*

Figure 5 - Curvilinear estimated relationship of LN Labor productivity on LN R&D Investment as percentage of GDP and optimal level of R&D intensity to maximize the labor productivity. *Source*: Coccia M. 2018f. Optimization in R&D intensity and tax on corporate profits for supporting labor productivity of nations, The Journal of Technology Transfer, vol. 43, n. 3, pp. 792-814.

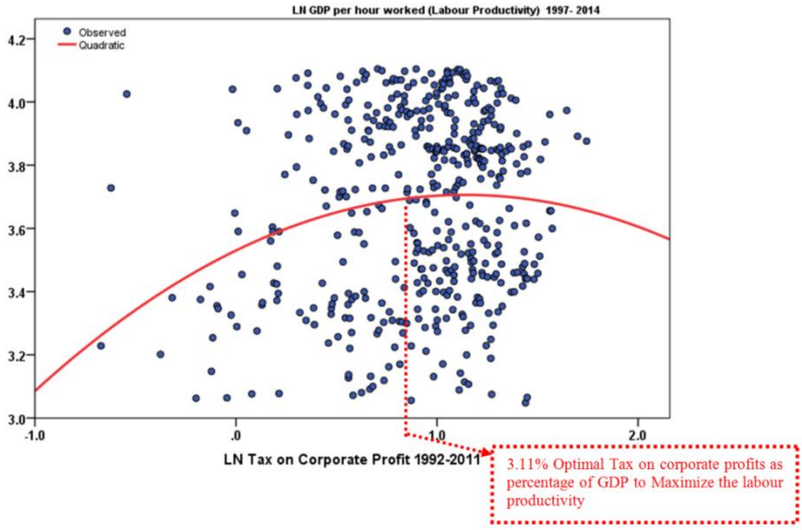


**Figure 6.** *LN GDP per hour worker (Labour productivity) 1997-2014*

Figure 6-Curvilinear estimated relationship of LN Labour productivity on Tax on corporate profits as percentage of GDP and optimal level of Tax on corporate profits to maximize the labor productivity. *Source*: Coccia M. 2018f. Optimization in R&D intensity and tax on corporate profits for supporting labor productivity of nations, The Journal of Technology Transfer, vol. 43, n. 3, pp. 792-814

Finally, table 3 suggests that leading geoeconomic regions with higher investments in R&D, in particular with higher private R&D expenditure, they foster a higher index of labor productivity.

**Table 3.** Research expenditure (a proxy of investment in science and scientific research) and labor productivity between worldwide players

| World Players | Public R&D Expenditure 1998-2008* [a)] | Private R&D Expenditure 1998-2008* [b)] | Labor productivity Index 2000=100 (1995-2009)** |
|---|---|---|---|
| EU (15 countries) | 0.66 (35%)[1)] | 1.25 (65%) | 101.64 |
| United States | 0.64 (24%) | 1.99 (76%) | 104.88 |
| Japan | 0.73 (23%) | 2.46 (77%) | 103.89 |

**Source:** * Eurostat (2010); ** OECD (2010); *Note*: a) R&D expenditures by government and higher education sector; b) R&D expenditures by business enterprise and private non-profit sector. 1) Percent value of the total.

## Discussion and concluding observations

Bernal (1939) argued that science is considered an "institution" in relation to social and economic events. Bush (1945) claimed that scientific progress is essential to nations and suggested basic principles for governments to support scientific research and higher education. On the basis of the study presented here, the scientific research is a main factor for nations to support socioeconomic power, wealth, economic growth, innovative outputs, etc. Coccia (2018) argues that high investment in scientific research in period of environmental threats can generate general purpose technologies and support long-run economic growth. This study also suggests that nations have a strong incentive to invest in scientific research because long-run consequences are a higher labor productivity and economic growth (cf., Coccia, 2017a).

Overall, then, humankind realized that science and scientific research mean socioeconomic power that in the long run generates many benefits in society (Coccia & Bellitto, 2018). This search for knowledge and investigation of the unknown then became the controlling mechanisms for many research projects in human society. Callon (1994) argues that public investment in R&D is needed to investigate emerging research fields, though results can be uncertain and/or achieved only in the long run, such as studies for measuring gravitational waves and detecting their sources in the universe. In fact, National Science Foundation in the USA has done a huge investment of more than $1 billion for Laser Interferometer Gravitational-Wave Observatory (in construction, operational costs and research funds for scientists) for studying gravitational waves, an unknown research field. In general, the impetus of nations to perform scientific research is to support progress with transfer to techno-economic processes and progressive social change directed to the adaptation of life to new economic and social bases. The interwoven relation between scientific research and new technology yields a greater satisfaction of human needs for improving wellbeing in society. In fact, scientific research of nations supports economic, technological and social change directed to satisfy human wants and human control of nature. Scientific research, combined with technology should be the forerunners of a full realization of the meaning and possibilities of life of individuals in society (cf., Woods, 1907; Coccia & Bellitto, 2018). Hence, it would be naive to limit the driver of scientific research or at least to make it dependent on the economic vector of nations alone. The scientific research is due to the expanding content of the human life-interests whose increasing realization constitutes progress, rather than external processes conceived in terms of economic processes. Scientific research is a means to support human progress in terms of long-run ideals to satisfy human interests that change in society and characterize the human nature from millennia (Woods, 1907, pp.813-815; Coccia & Bellitto, 2018). To put it differently, the whole process of scientific research, as reflection of society, is driven by the increasingly effective struggle of the human mind in its efforts to raise superior to the exigencies of the external world, as well as to satisfy human desires, solve problems and achieve/sustain power in society.

To conclude, scientific research is driven by complex factors mainly linked to the question of what human beings truly need and how they seek to address and satisfy real needs and ideals in their social context. This paper shows some determinants of scientific research of nations, such as the goal of achieving socioeconomic power, technological and scientific superiority, higher labor productivity, etc. However, the results and arguments of this study are of course tentative. In fact, the phenomenon is complex and analyses here are not sufficient to understand the comprehensive reasons for and the general implications of science in society, since we know that other things are often not equal over time and space. This preliminary analysis of the reasons inducing nations to perform scientific research may form a ground work for development of more sophisticated studies and theoretical frameworks, focusing on characteristics often neglected in social studies of science. Future efforts in this research field should provide more statistical evidence to support the theoretical framework here. To reiterate, the study here is exploratory in nature and findings need to be considered in light of their limitations. Overall, then, there is need for much more detailed research to shed further theoretical and empirical light on vital determinants supporting scientific research of nations in specific social and contestable environments.

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# 8. Competition between basic and applied research in the organizational behaviour of public research labs

## Introduction

The research sector (Senker, 2001) is undoubtedly one of the most controversial topics of political debate in many countries. The discussion concerns both public financing and organization. In fact, each country organises and manages public research institutions in order to increase the production of scientific research and technology transfer, more and more necessary to firms' competitiveness and economic growth (Romer, 1990). Generally speaking, scientific research is divided into basic and applied research. The first attempts at systematically defining these terms occurred in Britain in the 1930s, more precisely among those scientists interested in the social aspects of science. Frascati's manual (OECD, 1968) defines *Basic research* as experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts without any specific application or purpose. On the other hand, *Oriented-basic research* is carried out with the expectation of producing a broad base of knowledge likely to form the background to the solution of recognized or expected current or future problems or possibilities (Calvert, 2004).

As Needham (1959) says, there is no sharp distinction between "pure" and "applied" science: "There is really only science with long term promise of application and science with short term promise of application. True knowledge emerges from both kinds of science".

The problems we wish to tackle are the following: are there trade-offs between basic and applied research? What is the behaviour of research institutes in the production of scientific research?

To answer these important economic questions, the purpose of the paper is to investigate the relationship between basic and applied research, and the scientific behaviour of public research institutes in the production of scientific research. In particular, the paper analyses the presence of rivalries between basic and applied research within the institutes of the most important Italian public research institutions, the Italian National Research Council. These results may provide useful information to policy makers in order to assign specific objectives and improve the efficiency of these public research labs. The next paragraph describes the theoretical framework, while the third section deals with the methodology of the research. The fourth paragraph shows the results. The discussion and concluding remarks describe the causes of the phenomenon and the effects of these issues on the behaviour of public research bodies.

## Theoretical background

Nowadays when more and more political pressure is put on public research in order to boost its contribution to the common good (applied research) and to achieve more targeted effects by doing basic research in the fields of economy and society, many ask themselves how these objectives can be achieved without negative consequences on basic research[16]. In other words, several *policy makers* have raised the problem of how to encourage researchers working in public institutions to collaborate with private enterprises or to transform the basic research into applied research. This new approach of the researchers may generate competition between basic and applied research carried out within the institutes, even if the literature on economics of science and innovation argues that technical applications could be positively associated with scientific productivity (Stephan *et al.*, 2002, Van

[16] For other studies about processes of scientific research and technology in economic systems, as well as managerial and organizational behaviour of public research labs, cf., Calabrese *et al.*, 2005; Cariola & Coccia, 2004; Cavallo *et al.*, 2014, 2014a, 2015; Coccia, 2001, 2003, 2004, 2005, 2005a, 2005b, 2005c, 2006, 2006a, 2007, 2008, 2008a, 2008b, 2009, 2009a, 2010, 2010a, 2010b, 2010c, 2010d, 2010e, 2011, 2012, 2012a, 2012b, 2012c, 2012d, 2013, 2013a, 2014, 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2015, 2015a, 2015b, 2015c, 2015d, 2016, 2016a, 2016b, 2016c, 2017, 2017a, 2017b, 2017c, 2017d, 2018, Coccia & Bozeman, 2016; Coccia & Finardi, 2012, 2013; Coccia & Wang, 2015, 2016; Coccia & Cadario, 2014; Coccia *et al.*, 2015, 2012, Coccia & Rolfo, 2000, 2002, 2009, 2012, 2007, 2010, 2010, 2013; Coccia & Wang, 2015, 2016; Rolfo & Coccia, 2005.

Looy *et al.*, 2004) or with the number of quotes (Agrawal & Handerson, 2002; Diamond, 1986a). Van Looy *et al.* (2005) demonstrate that papers issued by departments focused on applied research activities are more science-oriented than those created by departments working on basic research. Among the most recent contributions, a number of studies analyses the relationship between scientists and industrial partners, who patent the results of their discoveries (David, 2000; Nelson, 2001; Mowery *et al.*, 2002). However, the analysis of the rivalry between different types of scientific research is connected to issues concerning the public nature of knowledge (Arrow, 1962) and the appropriate reward system to support basic research (Dasgupta & David, 1994; Gallini & Scothmer, 2001). Rivalry has been increasing also because it is the scientists' duty to manage the good called "knowledge", which can be used for several different purposes. In this sense, scientists are considered multi-objective agents, carrying out a wide set of activities, ranging from basic research to teaching, consulting, and so on (Levin & Stephan, 1991; Lach & Shankerman, 2003). Stephan *et al.* (2002) claim that there are very good reasons to believe that applied and basic research can be reciprocally supported. Carraro *et al.* (2001) and Fransman (2001) assert that some scientific discoveries derive from intense interactions between basic and applied research (science and technology) and it would be impossible to achieve them otherwise[17]. Calderini & Franzoni (2004) study rivalry issues (over a three-year period) on a panel of 1,323 Italian researchers operating in the field of engineering and materials science, adopting the number of the researchers' patents as the hypothesis for applied research. Using a negative binomial function, they show that the patenting activity (applied research) carried out during the same period or in earlier periods generates a positive impact on the number and quality of publications (basic research), both in the same period and in later periods. Studying the researchers within the Katholieke Universiteit Leuven, Van Looy *et al.* (2005) reach similar results.

[17] For other studies of sources of science, technology and research labs, cf., Calabrese *et al.*, 2005; Cariola & Coccia, 2004; Cavallo *et al.*, 2014, 2014a, 2015; Coccia, 2001, 2003, 2004, 2005, 2005a, 2005b, 2005c, 2006, 2006a, 2007, 2008, 2008a, 2008b, 2009, 2009a, 2010, 2010a, 2010b, 2010c, 2010d, 2010e, 2011, 2012, 2012a, 2012b, 2012c, 2012d, 2013, 2013a, 2014, 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2015, 2015a, 2015b, 2015c, 2015d, 2016, 2016a, 2016b, 2016c, 2017, 2017a, 2017b, 2017c, 2017d, 2018, Coccia & Bozeman, 2016; Coccia & Finardi, 2012, 2013; Coccia & Wang, 2015, 2016; Coccia & Cadario, 2014; Coccia *et al.*, 2015, 2012, Coccia & Rolfo, 2000, 2002, 2009, 2012, 2007, 2010, 2010, 2013; Coccia & Wang, 2015, 2016; Rolfo & Coccia, 2005.

To sum up, the economic analysis of the rivalry between basic and applied research has led to a series of non-univocal results, with remarkable differences among various scientific fields. Specifically, the problem seems to be related both to the indicators used (above all, patents) and to the time period selected for the analysis, as well as to the focus of the investigation, which is represented in the vast majority of cases by individual researchers (Diamond, 1986). Although some economists are aware of the rivalry existing between basic and applied research, there have been very few empirical tests and analyses concerning the causes and effects of the phenomenon. This weakness of the economic literature is a problem both from the managerial point of view and at the research policy level. Therefore, this paper investigates the rivalry between basic and applied research within the biggest Italian public research body, analysing the main determinants among different scientific fields and effects on economic systems in the long run. The results may provide information to policy makers in order to increase the efficiency of these structures and of the overall national system of innovation (Lundvall, 1992). The methodology is described in the following section.

## Materials and methods

The research uses data regarding 2000-2003 provided by the Italian National Research Council (CNR). CNR is a public research body (similar to the French *Centre National de la Recerche Scientifique*, to the German *Max-Planck Gesellschaft* and to the Spanish *Consejo Superior de Investigaciones Científicas*) which promotes, coordinates, and regulates Italian scientific research with the aim of advancing the Country's scientific and technological progress. Its 108 research institutes are public funded to produce scientific research according to general guidelines set by the Italian Government and the European Commission.

This paper investigates the relationship between applied and basic research, since this can affect the country's economic growth in the long run. First of all, the definition of scientific rivalry is given:

*Scientific rivalry is the increase of applied research and simultaneously the reduction of basic research with negative effects on economic growth in the long run.*

In this paper, the number of international publications and the total number of publications by researchers of the institutes are considered a proxy of basic research, while the institutes' technological transfer activities are considered a proxy of applied research. In particular, the paper uses the revenues deriving from technology transfer activities in the broad sense (Coccia & Rolfo, 2002), represented by: a) analysis and technical tests (chemical and physical); b) technological services (homologation, calibration, nuclear magnetic resonance, etc.); c) quality services (accreditation, certification, quality control, etc.); d) environmental services (water monitoring, pollutant emission control, etc.); e) information technology services (data elaboration, supply of databases and data, etc.); f) health services; g) research contracts with firms and institutions.

Patents are not used as an indicator of applied research because of low number of patents within the CNR. Consequently, technological transfer activities are preferred as proxy of applied research activities.

Therefore:

- The number of international publications and/or the total number of publications ($x_i$) are indicators of public laboratories' basic research;
- The financial income deriving from technological transfer activities ($y_i$) is an indicator of the institutes' applied research.

The above variables are identified in relation to each of the five scientific fields (basic, life, earth and environment, social and human, engineering and information sciences), in which the 108 CNR institutes were operating during the 2000-2003 period. The analysis of the rivalry is carried out using two methodologies: the non-parametric rank statistics and the concentration indices, to countercheck the previous results and to investigate the behaviour of public research institutes in depth.

In order to avoid the size of the institutes affecting these variables, the first step is the computation of the value pro-capita for each individual researcher in each institute. For researchers we intend only the payroll employees with the status of civil servants, associate researchers (belonging to universities), PhD candidates, and post-doc fellows are not included.

$$\bar{x}_i = \text{average value procapita of basic research i-th institute} = \frac{\text{variable (no. of publications) i-th institute}}{\text{researchers of the i-th laboratory}}$$

$$\bar{y}_i = \textit{average} \text{ value procapita of applied research i-th institute} =$$

$$= \frac{\text{variable (revenue from technology tranfer activities) i-th institute}}{\text{researchers of the i-th laboratory}}$$

In order to apply the first method, the research institutes are arranged in descending order (from the highest to the lowest value), according to the two above indicators of basic and applied research $(\bar{x}_i, \bar{y}_i)$, to create ordinal variables. The degree of relation of these two ordinal variables is measured by a non-parametric rank statistic: the rank correlation coefficients. This index is a measure of the strength of the association between two variables. We use these coefficients, since the scientific research and technology transfer carried out by the institutes are not easy to measure, for instance an institute can have a lower number of publications but of higher quality than another one. For this reason, we prefer to construct lists and not to indicate the accurate values, which are proportional variations of the intensity of the variables. Therefore, the variables $(\bar{x}_i, \bar{y}_i)$ are substituted by the values ($r_i$ and $s_i$) that express the ranks of the institutes. Then, $s'_i$, being the ranking number of $\bar{y}_i$ in the descending list, is calculated so that:

$$s'_i = N + 1 - s_i$$

where $N$ is the total number of cases. The main indices based on two ordinal variables are those of Spearman and Gini:

$$\text{Spearman rank correlation coefficient} = \rho = \frac{6\sum_{i=1}^{N}(r_i - s_i)^2}{N(N^2-1)}$$

Gini's rank correlation coefficient has the same aim as Spearman's index, and it is used in this paper to check the previous results. The formula is given by:

$$G = \frac{\sum_{i=1}^{N}\left|r_i - s'_i\right| - \sum_{i=1}^{N}\left|r_i - s_i\right|}{\left[\frac{N^2}{2}\right]}$$

The value of these indices is +1 when there is a perfect (positive) rank correlation, i.e. the highest relationship between the variables. The value is −1 when there is the lowest relationship between the variables.

To sum up, the following hypotheses are stated:

❑ if ρ or G are *negative* ⇒ there is *rivalry* between basic and applied research within public research institutions.

❑ if ρ or G are *positive* ⇒ there is *NO rivalry* between basic and applied research within public research institutions.

The second method used to investigate the behaviour of the institutes in the production of basic and applied research is the concentration index. In this case, the analysis is carried out considering absolute values rather than average values, which are used in the previous analysis. Since scientific fields of research are similar to sectors, this method is an effective analysis tool of scientific labs' behaviour. In fact, it shows, for each scientific field, whether institutes focusing on basic research are the same institutes as those focusing on applied research. The economic literature provides several measures for the magnitude of inequalities. One specific indicator is Gini's coefficient, which measures the degree of concentration (inequality) of a variable in a distribution of elements (Girone & Salvemini, 1988):

$$R = index\ \ of\ \ concentrat\ ion = \frac{\sum_{i=1}^{N-1}(p_i - q_i)}{\sum_{i=1}^{N-1} p_i}$$

Where $x_i$ = total number of elements of *i* case (e.g. number of Publications of *i-th* laboratory), $p_i$ is $i/N$ (N is the total number of elements), $A_i$ = cumulative values of $x_i$, while $q_i$ is $A_i / A_N$. Gini's coefficient ranges between 0, when there is no concentration (perfect equality), and 1 when there is total concentration (perfect inequality).

Moreover, this method considers 10% and 25% of the best-performing research institutes working on applied research to measure the cumulative percentage of their basic research. This measure is carried out per year and scientific field. Excel and SPSS® statistic packages are applied.

## Results

The structure of the Italian CNR (since 2001), after a reorganisation policy, is based on 108 institutes, which have 191 decentralised units. They operate in five scientific fields, which are the basis of 11 scientific departments: 1) Basic sciences, with research bodies operating in the field of mathematics, physics, and chemistry; 2) Life sciences, with institutes working in the field of medicine, biology, agriculture, and molecular biology; 3) Earth and environmental sciences (geology, environment, and habitat); 4) Social sciences and humanities, including institutions operating in the field of history, philosophy, and philology; law and political science; economics, sociology, and statistics; artistic heritage; 5) Technological sciences, engineering, and information technology, made up of structures operating in the field of engineering, architecture, technology, and information technology.

The results are presented for each of the five fields, due to the fact that each field has distinguishing structural features and scientific activities (tables 1 and 2).

- *Basic Sciences*

Basic sciences were made up of 28 research institutes of medium-large size, with an average number of researchers of 38.64 units and an average public funding of over 593,000 Euro (2000-2003 period). Year by year, the average number of employees increased, going from 28.61 in 2000 to the average value of 44.82 in 2003. Average funding decreased constantly through the years, going from over 615,000 Euro to around 560,000 Euro in 2003. This field has undergone prominent changes, from an initial state when Gini's and Spearman's indices showed absence of rivalry between basic and applied research to the scenario of more recent years, in which there is rivalry between basic and applied research. Spearman's index shows rivalry both in 2002 and in 2003, while Gini's index shows it in 2003 only.

- *Life Sciences*

With its 33 institutes, this was the field that included the highest number of institutes within CNR. They were usually of medium-large size, with an average number of employees of 34.99 units per institute during the 2000-2003 and an average amount of public funds of around 511,000 Euro. The mergers of different institutes, following the reorganisation started in 2001 and still ongoing as of today, have led to an increase in the average number of researchers per institute from 25.70 in 2000 to 42.09 in 2003. Similarly, to basic sciences, public funds dropped during the four-year period reaching less than 491,000 Euro in the last year. Both Spearman's and Gini's indices show that there is rivalry between basic and applied research with ups and downs every other year. Rivalry was lower in certain years (2000 and 2002) and higher in others (2001 and 2003).

- *Earth and Environmental Sciences*

This was the field of CNR with the smallest number of research institutes, numbering only 10; they were, however, of fairly large size, since the average number of researchers (in the 2000-2003 period) was considerably higher than in other fields, 45.02 researchers each, and the average financial resources were above 780,000 Euro. The institutes included in this field grew through the years, going from 36.20 units in 2000 to 55.90 units in 2003. As far as public funding was concerned, similarly to the other fields, there was a constant decrease as the years went by.

Both Gini's and Spearman's indices show an initial lack of rivalry between basic and applied research, that turned into a competitive situation in the last years of the period, proven more evidently by Spearman's index rather than by Gini's.

- *Social and Human Sciences*

This field included 19 research institutes of smaller size in comparison to the other fields: On average, during the four-year period, they had 14.81 units and the lowest financial resources among all the CNR institutes, less than 249,000 Euro. Through the years, the changes undergone by these institutes were the same as those taking place in other fields, with an increase in the average number of researchers (due to mergers) and the reduction of funding (due to the reduction in public financing for research activities enacted by Italian governments in the last decade). This is the only field that showed an initial situation of rivalry between basic and applied research, measured by the two indices, while in the following years there was a lack of rivalry. In fact, contrary to the other fields, here revenues deriving from technological transfer activities dropped off, while the number of international publications rose.

- *Technological, Engineering, and Information Technology Sciences*

This field includes 18 research institutes, which are of medium size in comparison to the other fields. The average number of researchers was 28.65 during the 2000-2003 period, while average public funding in the same period was over 551,000 Euro. As for the other fields, the average number of researchers rose constantly, while public financial resources decreased. Gini's and Spearman's indices show a constant rivalry between basic and applied research, even though the values decreased slightly through the years. These results are summarised in tables 1 and 2, which display a general overview.

**Table 1.** *Rank correlation coefficient of research institutes producing basic research* and applied research***

| | Arithmetic mean per researcher | |
|---|---|---|
| | *G* *Gini* | *ρ* *Spearman* |
| 2000 | 0.017147 | 0.044385 |
| 2001 | –0.125857 | –0.126764 |
| 2002 | 0.024691 | 0.072690 |
| 2003 | –0.035322 | –0.027875 |

* = measured by number of International publications;
**=measured by revenue from technology transfer activities.

**Table 2.** *Rank correlation coefficient between basic research* and applied research**- per scientific field and year*

| | *Scientific field* | *No. of institutes* | *Year* | *G Gini* | *ρ Spearman* |
|---|---|---|---|---|---|
| 1 | Basic sciences | 28 | 2000 | 0.148 | 0.162 |
| | | | 2001 | 0.128 | 0.055 |
| | | | 2002 | 0.020 | –0.008 |
| | | | 2003 | –0.204 | –0.284 |
| 2 | Life sciences | 33 | 2000 | –0.184 | –0.201 |
| | | | 2001 | –0.492 | –0.617 |
| | | | 2002 | –0.121 | –0.133 |
| | | | 2003 | –0.298 | –0.334 |
| 3 | Earth and environmental sciences | 10 | 2000 | 0.320 | 0.406 |
| | | | 2001 | 0.000 | –0.055 |
| | | | 2002 | –0.120 | –0.127 |
| | | | 2003 | –0.040 | –0.006 |
| 4 | Social sciences | 19 | 2000 | –0.122 | –0.126 |
| | | | 2001 | 0.188 | 0.253 |
| | | | 2002 | 0.022 | 0.072 |
| | | | 2003 | 0.244 | 0.332 |
| 5 | Engineering and Information and communication technologies sciences | 18 | 2000 | –0.235 | –0.302 |
| | | | 2001 | –0.148 | –0.222 |
| | | | 2002 | –0.037 | –0.065 |
| | | | 2003 | –0.123 | –0.187 |

* = measured by number of international publications;
**=measured by revenue from technology transfer activities.

- *Behaviour of the institutes in the production of basic and applied research*

This analysis is carried out first on an aggregate level and then divided by fields and years. The analysis of all the 108 institutes of the National Research Council of Italy shows that there has been a trend of concentration growth among the institutes producing applied research. Gini's concentration index (R) increased from 62.58% in 2000 to 69.53% in 2003.

On the other hand, the concentration of basic research decreased in the same period, going from 48.83% to 45.87% (Table 3).

**Table 3.** *Concentration index of basic research and applied research within the 108 Italian public research institutes (period 2000–2003)*

| *Years* | *Applied research* | *Basic research measured by International publications* | *Basic research measured by total publications* |
|---|---|---|---|
| 2000 | 62.58 | 48.83 | 42.95 |
| 2001 | 70.92 | 48.86 | 39.98 |
| 2002 | 71.12 | 47.08 | 40.59 |
| 2003 | 69.53 | 45.87 | 37.49 |

The competition between basic and applied research is present when considering 10% of the institutes with the best applied research performance (which, as stated above, is measured by the revenues resulting from technological transfer activities). In 2000, 10% of the research units produced 47.05% of the total applied research during that year. The same institutes, during the same year, produced only 18.45% of basic research (measured by total publications). This analysis, repeated in the following years, shows a growth trend in relation to the production of applied research that is a staggering 58.45% of the total in 2003, counterbalanced by a constant decrease in the production of basic research, which during the last year is a mere 13.27% of the total (Table 4).

**Table 4.** *Cumulative (%) of applied and basic research produced by 10% of the best-performing research institutes in applied research (period 2000-2003)*

| *Year* | *Applied research* | *Basic research measured by International publications* | *Basic research measured by total publications* |
|---|---|---|---|
| 2000 | 47.05 | 17.94 | 18.45 |
| 2001 | 60.01 | 14.66 | 14.71 |
| 2002 | 59.39 | 14.38 | 15.05 |
| 2003 | 58.45 | 12.95 | 13.27 |

The overall situation described above is actually rather diversified throughout the different fields. As far as applied and basic research are concerned, basic sciences have a substantial reduction in concentration during the 2000-2003 period. The concentration reduction trend can be observed in social sciences (even though initially there was a higher concentration in these two activities when compared to the previous field) and in technological, engineering and information technology sciences. Life sciences and earth and environmental sciences share a similar behaviour in their concentration indices: there is an increase in concentration of applied research, while basic research has an initial reduction followed by either an increase or a rising and falling trend (table 5). The analysis is repeated considering 25% of the institutes with the best applied research performance (which, as stated above, is measured by the revenues resulting from technological transfer activities). After that, the same institutes are also considered in relation to basic research, in their respective fields and years. The results display a high rivalry between basic and applied research over time within the institutes of all scientific fields (see table 5), except social sciences.

Table 5. *Concentration among 108 Italian public research units- per typology and year*

| *Year* | | *Scientific field* | *Concentration* — *Index of concentration*: *Applied research* | *Index of concentration*: *Basic research (measure by International publications)* | *Cumulative (%) of applied and basic research produced by 25% of the best-performing research institutes in applied research*: *Applied research* | *Cumulative (%)…*: *Basic research (measured by International publications)* |
|---|---|---|---|---|---|---|
| 2000 | 1 | Basic sciences | 60.70 | 38.48 | 68.27 | 34.75 |
| 2001 | | | 57.90 | 34.85 | 67.95 | 32.04 |
| 2002 | | | 59.31 | 32.66 | 68.34 | 31.24 |
| 2003 | | | 47.13 | 35.39 | 56.83 | 29.21 |
| 2000 | 2 | Life sciences | 60.23 | 34.48 | 64.03 | 21.89 |
| 2001 | | | 81.44 | 31.28 | 83.34 | 19.47 |
| 2002 | | | 79.62 | 32.06 | 82.56 | 26.37 |
| 2003 | | | 79.77 | 35.20 | 83.23 | 22.71 |
| 2000 | 3 | Earth and Environment Sciences | 50.05 | 38.00 | 63.80 | 36.09 |
| 2001 | | | 50.21 | 36.19 | 67.47 | 34.92 |
| 2002 | | | 49.05 | 44.92 | 63.02 | 29.51 |
| 2003 | | | 53.35 | 34.58 | 67.40 | 30.68 |
| 2000 | 4 | Social sciences | 74.52 | 51.49 | 82.97 | 20.90 |
| 2001 | | | 77.27 | 49.19 | 81.89 | 46.95 |
| 2002 | | | 63.28 | 41.00 | 72.33 | 31.03 |
| 2003 | | | 65.29 | 37.73 | 72.44 | 38.67 |
| 2000 | 5 | Engineering and Information and communication technologies sciences | 49.12 | 52.28 | 60.11 | 25.39 |
| 2001 | | | 51.13 | 50.71 | 63.56 | 28.79 |
| 2002 | | | 46.79 | 48.29 | 58.59 | 27.82 |
| 2003 | | | 47.75 | 46.37 | 59.53 | 23.39 |

## Discussion and concluding observations

The economic literature (Calderini & Franzoni, 2004; Van Looy *et al.*, 2005) shows that the applied research measured by patents has a positive impact on publications (basic research), but if the revenues deriving from technology transfer are considered as an indicator of applied research, the situation changes. In fact, this research shows a general rivalry between basic and applied research, in the sense that the latter seems to turn to the disadvantage of the former and vice versa.

Which are the causes of this rivalry? Why is the rivalry present in Natural Sciences (basic, life, earth and environmental, engineering and information technology sciences; the abbreviation used is NES) and absent in Social and Human Sciences (abbreviation used is SHS)?

The results of this research are the basis of the following *proposition:* The reduction of public funds is the cause of an increasing rivalry between basic and applied research: the main effect of reducing public funds is an increasing in applied research measured by the revenues deriving from technology transfer activities and decreasing scientific publications (basic research).

The research policy reform of the Italian Government has been cutting public funds to public research institutes (figure 1A and 1B). Simultaneously increasing political influences to encourage collaboration between research labs and firms/other institutions have the effect of increasing self-financing deriving from technology transfer (applied research). In fact, Italian researchers working in research laboratories of NES, with a Hawthorne effect, would like to show a higher efficiency, therefore they have changed their approach towards the market, seen now as an important source to gather financial resources that are necessary to the economic survival of research institutes. Now, the NES's researchers focus their scientific activity towards applied research and consultancy to firms and public institutions, since their scientific field produces outputs of immediate industrial use (Coccia & Rolfo, 2002). A shift towards applied research activities in NES has led to an increase in self-financing but also in the rivalry with basic research activities, measured by scientific publications, which have been decreasing. Most of the institutes operate as *quasi-business firms* (Etzkowitz, 2003) due to the fact that *working time* of researchers when choosing between basic and applied research is a normal good with a negative slope that brings about a trade-off between these two activities. Figure 1A shows a rivalry in Natural sciences – NES (basic, life, earth and environmental, engineering and information technology sciences). In the selected period (2000-2003), total revenues deriving from applied research rose considerably, while the production of basic research decreased slightly *(scientific rivalry gap),* even if within the NES there are basic, life, earth, environment, engineering, ICT sciences, which have different behaviours over time.

Why is this phenomenon absent in Social and Human Sciences (SHS)?

Since the SHS has limited relations with the market due to its particular researches in history, philosophy, philology, Latin literature, and so on, researchers can rarely find private patrons. Therefore, researchers focus their scientific activities on education, domestic and international publications and this behaviour has not affected the reduction in scientific productivity (Coccia & Rolfo, 2002, see Figure 1B).

Moreover, the increase of scientific productivity over time within SHS may be also due to the smaller size of this field in comparison to NES. In fact, the economic literature shows that smaller institutes are more efficient (Carayol & Matt, 2004; Coccia, 2005) and therefore more flexible to organisation and scenario changes.

The rivalry within the Italian CNR has his roots in the reorganisation and research policy of the Government, which has the aim of increasing the efficiency of the overall scientific organization by means of a concentration of the existing resources. The main result is the reduction of certain costs (personnel, rents, and so on), but in terms of output increase the effects seem very much ambiguous. In fact, cuts in public funds and the uncertainty of the research policy reform create some diseconomies of scale, due to the increased costs of co-ordination of decentralised units, with a negative influence on the productivity of publications (basic research).

The analysis carried out in this research on the relationship between basic and applied research is important, since it shows that the new Italian research policy has created hybrid research laboratories ("*with many characteristics of the business firm, except for the profit motive*"; Viale & Etzkowitz, 2004), which focus on consultancies and applied research rather than basic research. Public research laboratories are not business firms, they do not maximize the profit, but their scientific reputation. Moreover, they have a different institutional mission and produce scientific research which is a public good (Arrow, 1962); so, the Italian research policy that has been reducing basic research can has negative effects on competitiveness and the country's long-term economic growth (Hare & Wyatt, 1992; Callon & Foray, 1997). This also generates a low economic performance of the whole Italian system (e.g. low growth rate of GDP and so on, Coccia, 2005a). In fact, according to the modern theory of endogenous growth (Romer, 1990), the reduction of scientific research and therefore of innovation is not the best way to push the systems towards future patterns of economic growth.

# Appendix

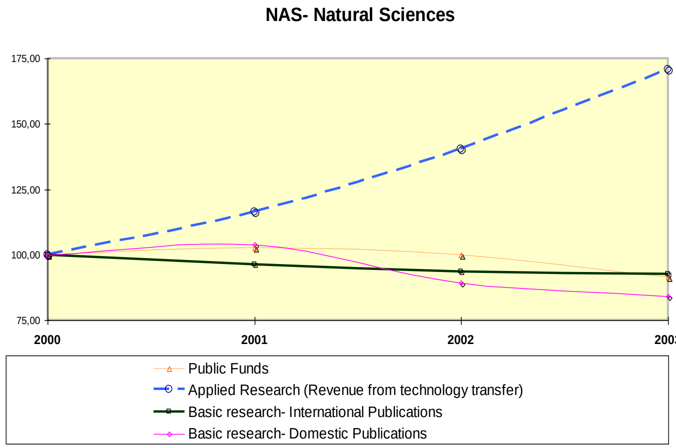


**Figure 1A.** *Dynamics of scientific research in NES over time (base 100=2000)*

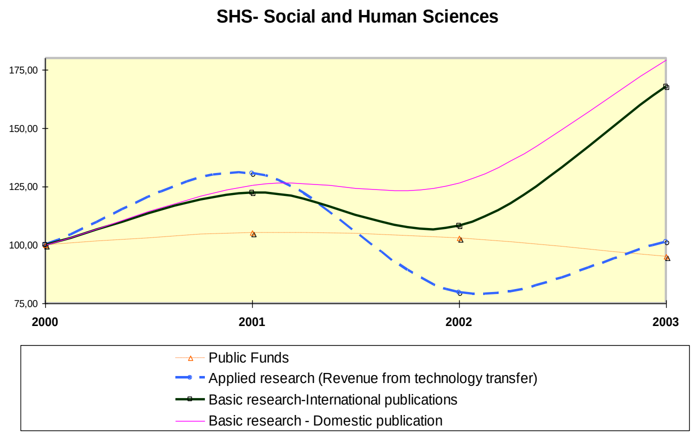


**Figure 1B.** *Dynamics of scientific research in SHS over time (base 100=2000)*

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# 9. Types of government and innovative performance of countries

## Introduction

The general determinants of socioeconomic and technological performance of nations are of profound interest in social and political sciences to understand the historical developmental paths over time. Many studies have analyzed several determinants of technical change and economic growth, such as the democratization (Coccia, 2010; Acemoglu *et al.,* 2008), demographic change and population (Coccia, 2014), religion and culture (Guiso *et al.,* 2003; Coccia, 2014a), energy systems (Coccia, 2010a; 2010b), climate (Smithers & Blay-Palmer, 2001; Coccia, 2015a), new products (Calabrese *et al.,* 2005; Cavallo *et al.*, 2014; 2014a; 2015; Coccia, 2016), institutional evolution (Acemoglu *et al.,* 2005), regulation of public action (Guenoun & Tiberghien, 2007), quality of local governance (Van Roosbroek & Van Dooren, 2010), political economy of R&D investments (Coccia, 2008, 2008a, 2008b, 2009, 2012, 2010c, 2013; Coccia & Rolfo, 2000; Rolfo & Coccia, 2005), technology transfer (Coccia, 2004, 2010d; Coccia & Rolfo, 2002; Cariola & Coccia, 2004), radical innovation (Coccia, 2016; 2016a, 2016b) scientific collaboration (Coccia & Wang, 2016; Coccia & Bozeman, 2016); reforms of central government (Adhikari *et al.,* 2012), etc. In general, institutions play a vital role in national innovation systems because they are one of the main elements of the complex network of economic agents that supports the process of technical advance in economy (Coccia, 2010). In particular, political institutions influence innovative activities by developing a set of laws, policies, norms, and infrastructures under which interactions between economic subjects, groups, and organizations take place for wealth creation and sustainability (*cf.*, Olstrom, 1990; Edquist, 2005; Spencer *et al.,* 2005). A theoretical framework linking national-level institutions to innovative activity differences across countries is the varieties of capitalism (VOC) approach by Hall & Soskice (2001).

The varieties of capitalism's (VOC) theory of technological innovation claims that variance in political institutions is the principal determinant of differences in national innovative behaviour: "more a polity allows the market to structure its economic relationships, the more the polity will direct its inventive activity toward industries typified by 'radical' technological change. Conversely, the more a polity chooses to coordinate economic relationships via nonmarket mechanisms, the more it will direct its inventive activity toward 'incremental' technological change" (Taylor, 2004, p.601). The state, the strengths of its authority and social power are important characteristics that influence economic systems, policy and relationships of economic subjects for fostering innovation and industries (Broberg *et al.,* 2013). In general, the leadership is a feature that can improve the technological and socioeconomic performances of complex organizations (Zaccaro, 2007; Makri & Scandura, 2010; Ryan & Tipu, 2013). However, in the varieties of capitalism's theory of technological innovation and in other theoretical frameworks, the concept and role of structure of executive, state power and leadership of government are generally absent (*cf.,* Taylor, 2004; Broberg *et al.,* 2013). Especially, in this research field, the relation between typologies of executive and technological performances of countries is hardly known. A main research question is *how* typologies of executive affect national level of innovative activity. The problem underlying this research question is to explain the institutional determinants of dissimilar technological and economic performance of countries. This study confronts this problem and endeavours to integrate whenever possible, the varieties of capitalism framework by analyzing the relation between types of executive and technological-socioeconomic performance of nations. In particular, this essay here has two goals. The first is to show that different patterns of technological innovations of nations may be also affected by dissimilar structures of executive. The second is to show that some typologies of executive can be more leadership-oriented, maintain political stability and support innovative activity of nations. Before analyzing and clarifying this socioeconomic issue, next sections present the theoretical background and methodology of this study.

## Theoretical framework

In economics of technical change, questions about the institutional causes of differences in technological performances of nations have remained at the periphery of research fields (Taylor, 2004). In this context, the varieties of capitalism's (VOC) theory of technological innovation makes its foray to explain cross-national differences of technological performances and dissimilar directions of technological progress among nations. VOC is a theory of capitalism in which: "some countries use markets more than others to coordinate economic actors and this variation is used to explain a myriad of comparative and international political-economic behaviour" (Taylor, 2004, p.603).

This theoretical framework argues that national institutions affect firms and other economic subjects by coordinating their socioeconomic activities. Countries in VOC theory can be either liberal market economies (LMEs), which are based on competitive market arrangements or coordinating market economies (CMEs) that are based on non-market arrangements of collaborating networks of interacting firms/economic subjects (Hall & Soskice, 2001). The variation of coordinating mechanisms can influence patterns of innovation and economic activity of countries. In particular, economic subjects (firms, universities, public research organizations, etc.) operating within LMEs tend to produce more radical innovation, where as economic subjects in CMEs tend to generate more incremental innovation (Hall & Soskice, 2001; Taylor, 2004; Broberg *et al.,* 2013, pp. 2575*ff*). An alternative framework in this research field is by Spencer *et al.*, (2005) that include the structure of the state and society:

> the structure of the state encompasses strong state structures where government authority is derived inherently from the state or weak state structures where government authority originates from the people. The structure of the society varies according to whether a country is organized along the interest of individuals (i.e., associational structures) or to the interests of groups of individuals (i.e., corporatists)-(Broberg *et al.,* 2013, p.257).

Spencer *et al.,* (2005) argue that different features of the structure of state and society generate four institutional types of nations: State corporatist, Social corporatist, Liberal pluralist and State nation. These theories have not been confirmed in empirical studies (Taylor, 2004; Broberg *et al.,* 2013). While the validity of certain of criticisms may be debated, it is clear that there are at least some facts about differences of technological performances of countries that these approaches have trouble explaining. The general consensus among scholars is that the varieties of capitalism's theory of innovation and theory by Spencer *et al.,* (2005) are in need of additional explanatory elements that better explain economic and innovation differences across countries (*cf.,* Campbell & Pedersen, 2007; Broberg *et al.,* 2013, pp. 2575*ff*).

A main variable, not included in these theoretical frameworks, is the leadership based on the structure of executive (Zaccaro, 2007; Avrey *et al.,* 2006; *cf.,* Klavans & Boyack, 2008). As a matter of fact, the examination of the relation between leadership and innovation is basic since leader systems can positively influence innovation processes and innovative activities of economic subjects (*cf.,* Howell & Avolio, 1993).

Leadership is defined in terms of: "(a) influencing individuals to contribute to group goals and (b) coordinating the pursuit of those goals… leadership as building a team and guiding it to victory" (Van Vugt *et al.,* 2008, pp.182-3). "Leadership is a solution to the problem of collective effort –the problem of bringing people together and combining their efforts to promote success and survival" (Kaiser *et al.,* 2008, p.96). Some studies argue that the leadership is a universal feature of human societies, which affects the population and citizens in important ways (Van Vugt *et al.,* 2008, p.182; Bennis, 2007). In fact, "Leadership… has a long evolutionary history… Arguably, individual fitness would be enhanced by living in groups with effective leadership (Van Vugt *et al.,* 2008, p.184). Leadership is also a system of relationships that involves the power in varying degrees in organizations (*cf.,* Hollander & Offermann, 1990). Galton defined leadership with two main features (as quoted by Zaccardo, 2007, pp.6*ff*): 1) as a unique property of extraordinary individuals whose decisions are capable of sometimes radically changing the streams of history; 2) the unique attributes of such individuals in their inherited or genetic makeup (*see* Zhang *et al.,* 2009 for the genetic basis and gene-environment interactions on leadership role). Arvey *et al.,* (2006, pp.2-4) claim that the leadership role occupancy is associated with genetic factors influencing the personality variables, such as social potency and achievement of specific goals. "Galton… argued that the personal qualities defining effective leadership were naturally endowed, passed from generation to generation" (Zaccaro, 2007, p.6). The leadership is in general affected by the situational context (*cf.* Vroom & Jago, 2007, pp. 17*ff*) and social environment around economic subjects (Zhang *et al.,* 2009). In fact, Porter & Mc Laughlin (2006, p.559) state that: "leadership in organization does not take place in a vacuum. It takes place in organizational contexts".

Many studies argue that the leadership is one of the most important determinants for improving innovation and performance in organizations. Jung *et al.,* (2003) show a positive linkage between style of leadership, called "transformational", organizational innovation and innovation-supporting organizational climate. Krause (2004) considers the leadership in terms of specific factors of influence (such as granting freedom and autonomy, openness of the decision-making process, etc.) forinnovative behaviour of organizations. Other scholars, such as Makri & Scandura (2010, pp.85-86), show that the leadership seems tobe an important driver of firm's ability to innovate. Carmeli *et al.,* (2010) confirm that the leadership significantly enhances the performance of firms. In particular, transformational leadership tends to be a catalyst in enhancing organizational outcomes and innovation propensity (Ryan & Tipu, 2013; Gardner & Avolio, 1998; Howell & Avolio, 1993). In short, the examination of the leadership–innovation connection is important in advancing and developing country context in the presence of intense competition, institutional instability and macroeconomic volatility (Tybout, 2000).

Although the vast literature in these topics, social studies lack of an integrative theoretical framework, which explains the relation between the leadership in the structure of executive and technological performances of countries. In fact, type of executive and dominant political class can play a main role for socioeconomic performances of nations. Mosca (1933) showed that the politicians can be considered as leader entrepreneurs and their activities are similar to political enterprises (*cf.,* Schumpeter (1975 [1942]). Weber (1919) argued that the essence of democracy consists of having charismatic leaders, which can be able to contrast the powers of the bureaucracy, to affect political institutions and support policy and economic outcomes (*cf. also* Persson & Tabellini, 2001). In general, several studies show that political structures can affect, positively or negatively, economic development of nations (Radu, 2015; Coccia, 2010). Some important typologies of executive in the geopolitical structure of nations are as follows:

1. Monarchy is a form of executive in which a group, usually a family called the dynasty, embodies the country's national identity and one of its members, called the monarch, exercises a role of sovereignty.
2. Parliamentary monarchy is a state headed by a monarch who is not actively involved in policy formation or implementation but it has a main institutional role; governmental leadership (formally) is carried out by a cabinet and its head –such as a

prime minister, premier, etc. - who are drawn from a legislature (parliament).

3. Mixed executive can be a parliamentary system of government: the executive branch of government has the direct or indirect support of the parliament (vote of confidence). Parliamentary systems usually have a head of government and a head of state. The head of government is the prime minister, who has the real power.

This theoretical background shows that the national institutions, the structure of executive and associated leadership can play a vital role in economic and social activity of nations. This study here endeavours to integrate whenever possible, the theoretical frameworks of VOC and Spencer *et al.,* (2005) by analyzing the relation between typologies of executive and innovative activities to explain the difference in technological and socioeconomic performances of countries. The following sections present methodology and results about this *nexus (connection)* to clarify, as far as possible, one of contributing factors that affects the socio-economic progress and dissimilar historical developmental paths of nations.

## Methodology and working hypothesis

Suppose that:

1. A *nation* is a system that can produce the same outcome in different ways.
2. *Monarchy and parliamentary monarchy* are based on stronger authority and leadership-oriented structure of executive.
3. *Mixed executives* are a type of government of nations *not* based on leadership-oriented government and with lower social power.
4. The focal hypothesis of this study is:
   *Hypothesis α (HP α)*: Nations with leadership-oriented executives (Monarchy and Parliamentary Monarchy) have higher technological and economic performances than Mixed executive (not leadership-oriented executive), *ceteris paribus*.

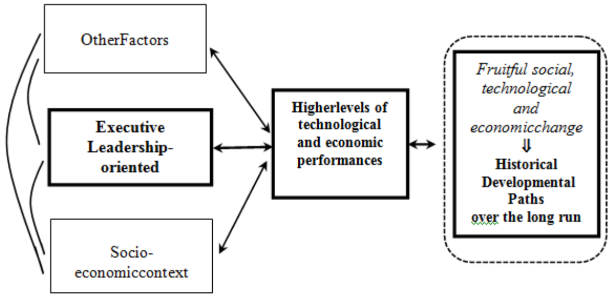


**Figure 1.** *Linkages between leadership-oriented executive and high levels of technological and economic performances of nations*

The purpose of the present study is to see whether the statistical evidence supports this hypothesis *α* that leadership-oriented executives are positively associated with higher technological and economic performances as represented in figure 1.

The source of Data is the Democracy Time-series Dataset by Norris (2008). The sample is based on all countries present in this dataset (Norris, 2008). The period under study is over 2010s. The study here considers the following classification of executive: parliamentary monarchy and monarchy that are assumed to be leadership-oriented executives, whereas mixed executive is supposed to be a not leadership-oriented executive. In particular, Monarchy in the study here includes 13 countries; Parliamentary Monarchy includes 31 countries and Mixed executive includes 92 countries that for the sake of briefness, the list is not described in Appendix A.

The socio-economic variables and related years under study are:

– Gross Domestic Product (GDP) per capita purchasing power parity (PPP) annual by World Bank (2008). GDP is a measure of the economic activity. It is defined as the value of all goods and services produced minus the value of any goods or services used in their creation.
– Human Development Index (HDI) 2002 year (UNDP, 2004). The HDI is a summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and have a decent standard of living. The HDI is based on three dimensions: The health dimension is assessed by life expectancy at birth; the education dimension is measured by mean of years of schooling for adults aged 25 years and more and expected years of schooling for children of school entering age; the standard of living dimension is

measured by gross national income per capita. The scores for the three HDI dimension indices are then aggregated into a composite index using geometric mean of normalized indices for each of the three dimensions (UNDP, 2016).

– Kaufmann political stability 2006. It measures perceptions of the likelihood that the government will be destabilized or overthrown by unconstitutional or violent means, including political violence and terrorism (WGI, 2016; Thomas, 2010).
– A main proxy of the technological potential of countries is the Energy consumption in Kilograms per capita and Electric power production (KWh) per capita.

The preliminary statistical analysis is performed with Arithmetic mean and Standard Deviation (SD) of these variables per typology of executive. Normality of distributions is checked with skewness and kurtosis coefficients. A logarithmic transformation is performed, when necessary, to obtain a normal distribution and apply correctly statistical analyses. The descriptive statistics are also represented with bar charts with average values of variables on *y*-axis and typology of executive on *x*-axis.

The main statistical analysis of this study compares the arithmetic means of key variables between specific executives by applying the Independent Samples *T* Test: this parametric test compares the means of two independent groups (*e.g.,* Monarchy/Parliamentary Monarchy *vs.* Mixed Executive) in order to determine whether the associated population means of variables among these sets of countries are significantly different. The null hypothesis ($H_0$) and alternative hypothesis ($H_1$) of the independent samples *T* test here are given by:

$H_0$: $\mu_1 = \mu_2$ (*i.e.*, arithmetic mean of Monarchy/Parliamentary Monarchy *is* equal to Mixed Executives)

$H_1$: $\mu_1 \neq \mu_2$ (*i.e.,* arithmetic mean of Monarchy/Parliamentary Monarchy is *NOT* equal to Mixed Executives)

This technique is a simple and reliable test to see whether statistical evidence supports the hypothesis $\alpha$ that nations governed by leadership-oriented executives (*e.g.,* Parliamentary Monarchy and Monarchy) have higher technological and economic performances than countries with Mixed executives (a not leadership-oriented executive), *ceteris paribus*. Statistical analyses are performed by means of the Statistics Software SPSS® version 15.0.

## Statistical evidence

This section endeavours to substantiate the hypothesis *α* underlying the model of Figure 1. This study, as said above, hypothesizes that nations with a leadership-oriented executive, *e.g.,* Monarchy and Parliamentary Monarchy, have levels of socioeconomic and technological performances higher than Mixed Executives over time. Results of the descriptive statistics per typology of executive are in table 1.

**Table 1.** *Descriptive statistics of variables per typology of executive*

| Classification of executive | | GDP per capita U$ | Human Development Index 2002 | Kaufmann Political Stability 2006 | Energy Consumption Kg per Capita | Electric power production (KWh) Per Capita |
|---|---|---|---|---|---|---|
| Parliamentary Monarchy | Mean | $11,055.52 | 0.83 | 0.597 | 3,434.97 | 16,121.58 |
| | SD | $9,808.20 | 0.13 | 0.829 | 3,432.64 | 30,614.85 |
| Monarchy | Mean | $7,374.17 | 0.71 | 0.336 | 5,973.11 | 6,985.32 |
| | SD | $5,512.96 | 0.13 | 0.721 | 7,912.94 | 12,226.46 |
| Mixed Executive | Mean | $5,757.65 | 0.68 | –0.189 | 1,523.56 | 5,531.86 |
| | SD | $6,668.25 | 0.18 | 0.975 | 2,198.42 | 12,007.55 |

**Note:** SD is Standard Deviation

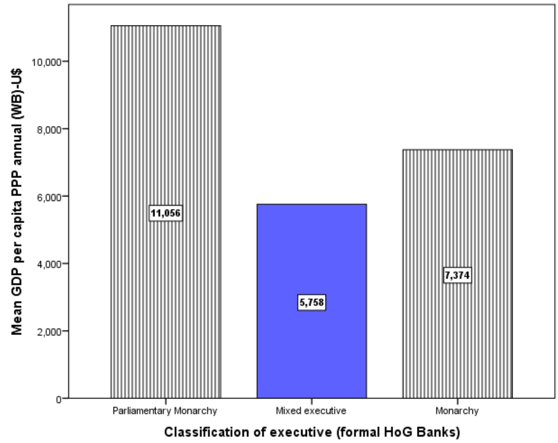


**Figure 2.** *Average GDP per capita in U$ per typology of executive*

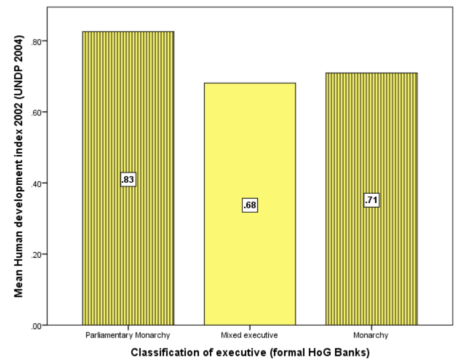


**Figure 3.** *Average index of Human Development per typology of executive*

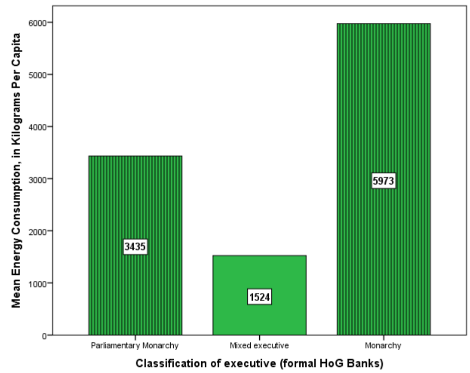


**Figure 4.** *Average energy consumption (kg per capita) pertypology of executive*

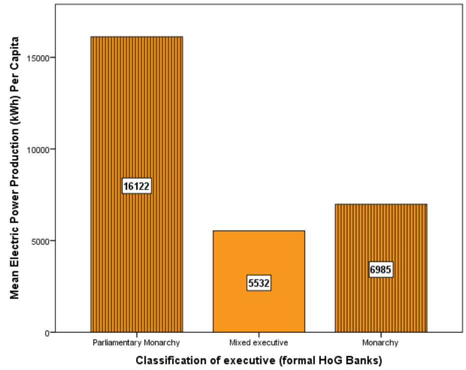


**Figure 5.** *Average electric power production (in kwh per capita)per typology of executive*

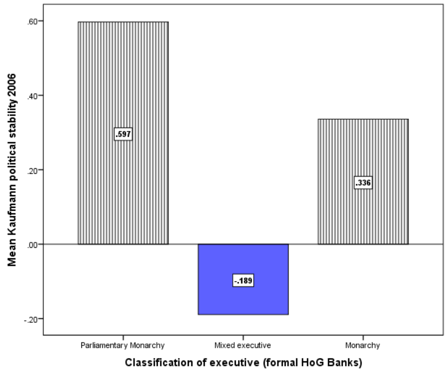


**Figure 6.** *Average Kaufmann political stability 2006 per typology of executive*

Figures 2-5 show that nations with parliamentary monarchy/monarchy have higher average levels of GDP per capita, HDI, and proxies of technological and economic performances.

One of the contributing factors that explains these results can be due to higher political stability of monarchy and parliamentary monarchy than mixed executive (*cf.* Tab. 1 and Fig. 6).

A logarithmic transformation is performed on some indicators to have normality of distribution and apply correctly further statistical analyses. Table 2 shows that the p-value of Test for Equality of Means (equal variances not assumed) is $p < 0.05$. In particular, considering this test, there is a significant difference at 5% in arithmetic mean performance of human development index (HDI), GDP per capita, electric power production and energy consumption per capita between countries with parliamentary monarchy/monarchy and mixed executive.

In short, results here seem to show that countries with leadership-oriented executives (*e.g.,* Parliamentary Monarchy and Monarchy) have a significant (statistically) higher average levels of economic and technological performance than countries with Mixed executive.

Table 2. *Independent Samples Test*

| | | Levene's Test for Equality of Variances | | *T*-test for Equality of Means | | |
|---|---|---|---|---|---|---|
| **LN GDP per capita PPP annual** | | | | | | |
| Parliamentary Monarchy and Mixed executive | Equal variances assumed | 25.024 | 0.00 | 17.727 | 2614 | 0.00 |
| | Equal variances not assumed | | | 18.572 | 1651.818 | 0.00 |
| Mixed executive and Monarchy | Equal variances assumed | 23.605 | 0.00 | −7.219 | 2133 | 0.00 |
| | Equal variances not assumed | | | −8.152 | 454.784 | 0.00 |
| **Human development index 2002** | | F | Sig. | *T* | df | Sig. (2-tailed) |
| Parliamentary Monarchy and Mixed executive | Equal variances assumed | 195.576 | 0.00 | 21.14 | 3052.00 | 0.00 |
| | Equal variances not assumed | | | 24.62 | 2225.60 | 0.00 |
| Mixed executive and Monarchy | Equal variances assumed | 58.702 | 0.00 | −2.82 | 2555 | 0.005 |
| | Equal variances not assumed | | | −3.58 | 619.999 | 0.00 |
| **LN Kaufmann political stability 2006** | | | | | | |
| Parliamentary Monarchy and Mixed executive | Equal variances assumed | 2.742 | 0.102 | 2.162 | 68 | 0.034 |
| | Equal variances not assumed | | | 2.321 | 66.361 | 0.023 |
| Mixed executive and Monarchy | Equal variances assumed | 2.887 | 0.096 | −1.418 | 48 | 0.163 |
| | Equal variances not assumed | | | −2.219 | 14.699 | 0.043 |
| **LN Energy consumption in kg per capita** | | | | | | |
| Parliamentary Monarchy and Mixed executive | Equal variances assumed | 30.271 | 0.00 | 11.958 | 1458 | 0.00 |
| | Equal variances not assumed | | | 13.031 | 848.020 | 0.00 |
| Mixed executive and Monarchy | Equal variances assumed | 12.916 | 0.00 | −6.854 | 1230 | 0.00 |
| | Equal variances not assumed | | | −5.965 | 204.485 | 0.00 |
| **LN Electric power production (KWh) per capita** | | | | | | |
| Parliamentary Monarchy and Mixed executive | Equal variances assumed | 13.783 | 0.00 | 14.722 | 2533 | 0.00 |
| | Equal variances not assumed | | | 15.351 | 1402.081 | 0.00 |
| Mixed executive and Monarchy | Equal variances assumed | 17.344 | 0.00 | −6.058 | 2135 | 0.00 |
| | Equal variances not assumed | | | −6.707 | 458.473 | 0.00 |

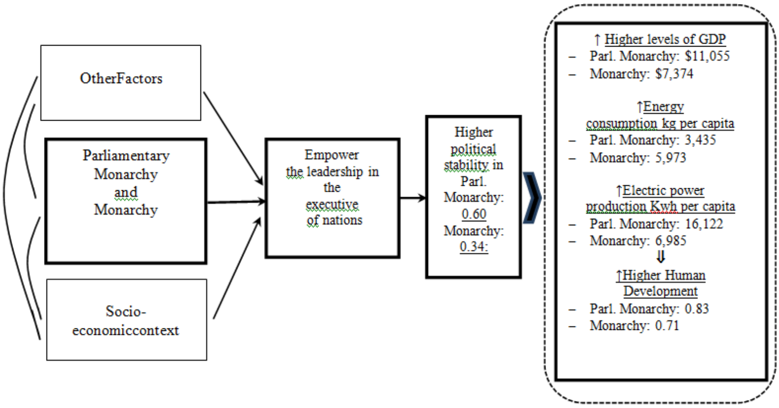


**Figure 7.** *Empirical results of the linkage between Monarchy and Parliamentary Monarchy Executive and higher average levels of technological and economic performances, ceteris paribus*

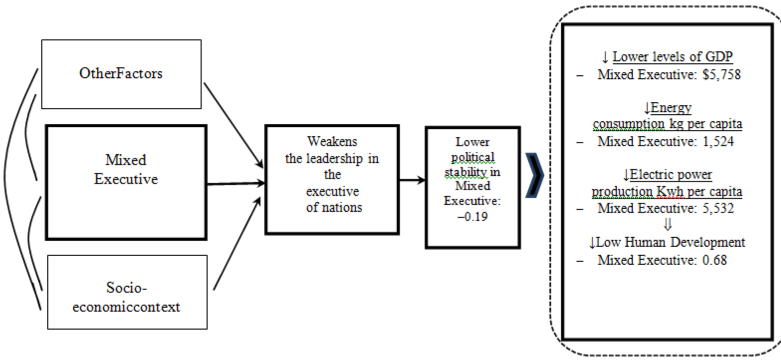


**Figure 8.** *Empirical results of the linkage between Mixed executive and lower average levels of technological and economic performances, ceteris paribus*

Hence, parliamentary monarchy/monarchy nations seem to have average levels of socioeconomic and technological performances higher than countries with mixed executive. These results are consistent with the hypothesis *α* stated above about the possible (*positive*) effect of leadership-oriented executives on technological and economic performances of nations, *ceteris paribus*. This result can be due to some systematic factors of nations, such as the higher political and economic stability of nations with a structure of executive based on parliamentary monarchy and monarchy (*see* Tables. 1-2; Fig. 6). These findings, based on statistical evidence, are synthesized in the figure 7 and 8. This study now moves on to discuss the results, trying, as far as possible, to clarify the relation between leadership-oriented executive and socioeconomic - technological performances of nations.

## Discussion and concluding observations

Understanding the determinants of innovation is a key goal of the economics of technological change to explain dissimilar technological and economic performances of nations. One of the main problems in this research field is *how* the structure of executive affects national level of innovative activities. The study here can provide a conceptual integration of the VOC and Spencer *et al.,* (2005) theoretical framework arguing that some typologies of structure of executive, leadership-oriented, can influence (*positively*) innovative activities of countries (fig. 10). Specifically, statistical evidence above seems in general to support the hypothesis $\alpha$ stated in the methodology that higher average levels of GDP per capita, energy consumption and electric power production per capita (proxy of economic and technological performances) of nations can be also explained by specific leadership-oriented executives, *e.g.* Monarchy and Parliamentary Monarchy, which induce a higher political stability over the long run, *ceteris paribus* (*cf.,* Guarini & Pattaro, 2016). *Vice versa*, countries based on mixed executives can have a weak leadership in the structure of government that generate a political instability and, as a consequence, lower levels of economic and technological performances.

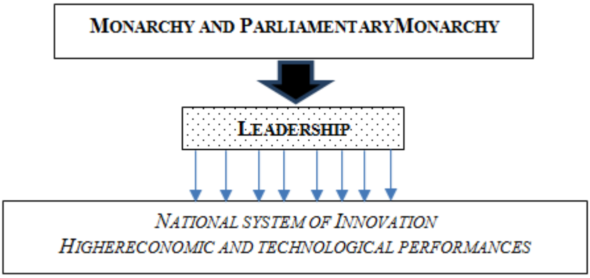


**Figure 10.** *Percolation of leadership by specific structures of executive that support higher levels of technological and economic performances of nations, ceteris paribus*

As debate surrounds the adequacy of the VOC theory of innovation and Spencer *et al.,* (2005) theoretical framework, the study's findings here suggest that the structure of government of countries may be a critical factor to explain some differences of innovative activities. In short, a clear and stronger leadership in executives of countries seems to be a main factor for supporting political stability and higher technological and socioeconomic performances over time. Broberg *et al.,* (2013) argue that: "national political institutions typified by strong state authority and corporatist societies were found to create higher levels of applied innovative activity". Ryan & Tipu (2013) show that: "active leadership has a strong and significant positive effect on innovation propensity, while passive-avoidant leadership has a significant but weakly positive effect on innovation propensity" (*cf.,* Fernandez *et al.,* 2008).

One of the contributing factors of this positive relation between parliamentary monarchy/monarchy and higher levels of economic and technological performance can be due to longer political stability of countries with leader ship-oriented executives. In fact, political stability has a positive effect on economic growth and other socioeconomic activities (*cf.,* Hussain Tabassam *et al.,* 2016).

This study provides some contributions to the socioeconomic literature on these topics, such as:

(1) A conceptual integration of VOC and Spencer *et al.,* (2005) theoretical framework by considering a new theoretical linkage between typologies of executive and a broader set of innovative and economic performances of countries (*e.g.,* GDP per capita, energy consumption and electric power production per capita).

(2) The conceptual framework here assigns a central role to the executive leadership-oriented, which is a factor neglected by certain of the dominant approaches to clarify contributing factors of higher levels of innovative activities and differences of technological – socioeconomic performances of nations;

(3) The conceptual framework here seems in general to show that specific types of executive, *e.g.* Monarchy and Parliamentary Monarchy established by Constitution and law, support a clearleadership of government that induces longer political stability, higher wealth and innovative activitiesover the long run;

This conceptual framework seems to be consilient (Thagard, 1988, Chp. 5), since it explains a greater number of socio-economic facts concerning higher technological performances of nations. Moreover, the simple elements of the study here are well known in economic and social sciences. The idea that leadership is associated with fruitful technological performance is not new and already used in social and political sciences (Jung *et al.,* 2008; Krause, 2004). However, the idea that leadership-oriented executives may be one of contributing factors that influences the political stability has not been used in literature to explain the different patterns of technological and economic performance across nations over time.

The characteristic of *analogy* of the results here is well-established in many studies of management and industrial organization (*cf.,* Makri & Scandura, 2010; Carmeli *et al.,* 2010; Nelson, 1999).

In short, the typology of executive can help to explain differences between-countries innovative performances and can be a main factor to be considered in VOC and Spencer *et al.,* (2005) theories.

Perhaps the most interesting finding of this study is that Monarchy and Parliamentary Monarchy, rather than Mixed Executive support longer political stability, higher innovative activities and fruitful historical developmental paths.

However, the current study here is exploratory in nature and examines only a limited number of variables. Moreover, the findings are contest-dependent because the geo-political structure of countries can change over time and space. Although this study offers important contributions to knowledge in these research fields, the study's findings need to be considered in light of their limitations. In fact, countries *within* the same political regime and type of executive have a high heterogeneity due to structural differences in political, cultural and social system that affect the technological and economic performances. Hence, some results discussed here should be considered with great caution because they are based on aggregate data of different countries with the same typology of executive. To exploring the general implications of this study, future research should also consider some controls and intervening variables that may be useful in providing a deeper and richer explanation of these phenomena of interests (e.g., institutional contexts, electoral systems, level of democratization, etc.).Future efforts could also examine other techno metrics that more closely related to innovative activities.

Overall, then, the results of this study are of course tentative, since we know that other things are often not equal over time and space. In particular, more fine-grained studies will be useful in future, ones that can more easily examine other complex factors of socioeconomic systems that explain the dissimilar economic performance within and outside the same political regime and type of executive. Much work remains to understand the complex relations between executive of nations, their internal and external leadership and technological -socioeconomic performance to provide additional explanatory elements for a comprehensive VOC and Spencer *et al.,* (2005) theory. To conclude, most of the focus here is on some typologies of executives and variables, clearly important, but not sufficient for broader understanding of *how* political - institutional structures affect national level of innovative activity of several nations over the long run.

# Appendix

**Table 1A.** *Countries with Type of Executivein 2003*

| Monarchy | | Parliamentary Monarchy | |
|---|---|---|---|
| Country | Region | Country | Region |
| Bahrain | Middle East | Andorra | Western Europe |
| Bhutan | Asia-Pacific | Antigua & Barbuda | South America |
| Brunei Darussalam | Asia-Pacific | Australia | Asia-Pacific |
| Jordan | Middle East | Bahamas | South America |
| Kuwait | Middle East | Barbados | South America |
| Monaco | Western Europe | Belgium | Western Europe |
| Morocco | Middle East | Belize | South America |
| Nepal | Asia-Pacific | Cambodia | Asia-Pacific |
| Oman | Middle East | Canada | North America |
| Qatar | Middle East | Denmark | Scandinavia |
| Saudi Arabia | Middle East | Grenada | South America |
| Swaziland | Africa | Jamaica | South America |
| Tonga | Asia-Pacific | Japan | Asia-Pacific |
| | | Lesotho | Africa |
| | | Liechtenstein | Western Europe |
| | | Luxembourg | Western Europe |
| | | Malaysia | Asia-Pacific |
| | | Netherlands | Western Europe |
| | | New Zealand | Asia-Pacific |
| | | Norway | Scandinavia |
| | | Papua New Guinea | Asia-Pacific |
| | | Samoa | Asia-Pacific |
| | | Solomon Islands | Asia-Pacific |
| | | Spain | Western Europe |
| | | St. Kitts & Nevis | South America |
| | | St. Lucia | South America |
| | | St. Vincent & Grenadine | South America |
| | | Sweden | Scandinavia |
| | | Thailand | Asia-Pacific |
| | | Tuvalu | Asia-Pacific |
| | | United Kingdom | Western Europe |

**Note:** Mixed Executives are not reported due to the long list of countries. Other types of executive, *e.g.* Presidential Republic, are not considered because data are misleading.

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# 10. Disruptive firms and industrial change

## Introduction

Current economies show the advent of many technological advances in information technology, biotechnology, nanotechnology, etc. that generate corporate, industrial and economic change (Arora *et al.,* 2001; Henderson & Clark, 1990; Nicholson *et al.,* 1990; Teece *et al.,* 1997; Van de Ven *at al.,* 2008; von Hippel, 1988). The literature in these research fields has suggested several approaches to explain the technological and industrial change, such as the theory by Christensen (1997, 2006) that introduces the concept of disruptive technologies of new entrants that disrupt the competitive advantage of incumbents in the presence market dynamisms. This theory explains the industrial change with the interplay between incumbent and entrant firms that can generate path-breaking Technologies (Ansari *et al.,* 2016; King & Baatartogtokh, 2015; Chesbrough & Rosenbloom, 2002; Christensen, 1997, 2006; Christensen *et al.,* 2015; Danneels, 2004, 2006; Gilbert & Bower, 2002; Hill & Rothaermel, 2003; Jenkins, 2010; King *et al.,* 2015; Ryan & Tipu, 2013; Tellis, 2006; Wessel & Christensen, 2012). While the validity of certain of these studies may be debated, it is clear that there are at least some facts about industrial change that theory of disruptive technologies has trouble explaining. As a matter of fact, current dynamics of industries shows that new entrants can generate disruptive technologies but their development and diffusion between markets have more and more economic barriers (Coccia, 2016; 2017).

This paper suggests that industrial change is driven by specific subjects -disruptive firms, rather than disruptive technologies per se. This study can be useful for bringing a new perspective to explain and generalize one of the sources of technological change that is represented by specific firms that have the potential to generate and/or to develop radical innovations that disrupt current products in markets and support industrial, economic and social change.

In order to position this study in existing approaches, the paper develops the theoretical framework in next section.

## Theoretical framework

Many industries are characterized by incumbents that focus mainly on improving their products and services (usually most profitable), and entrants that endeavor to develop new technologies in market segments, delivering market performance that incumbents' mainstream customers require (Christensen *et al.,* 2015; Christensen, 1997). In this context, Christensen (1997) argues that disruptive innovations generate significant shifts in markets (cf., Henderson, 2006). In particular, disruptive innovations are generated by small firms with fewer resources that successfully challenge established incumbent businesses (Christensen *et al.,* 2015). New firms can generate competence-destroying discontinuities that increase the environmental turbulence, whereas incumbents focus mainly on competence-enhancing discontinuities that decrease the turbulence in markets (cf., Tushman & Anderson, 1986). Scholars also argue that the ability of incumbents to develop and to market disruptive innovations is due to their specific ambidexterity: competence-destroying and competence-enhancing based on simultaneous exploratory and exploitative activities to support both incremental and radical innovations (Danneels, 2006; Durisin & Todorova, 2012; Lin & McDonough III, 2014; O'Reilly III & Tushman, 2004, 2008; cf., Henderson, 2006; Madsen & Leiblein, 2015) [18]. Disruptive innovations generate main effects both for consumers and producers in markets and society (Markides, 2006, pp. 22-23; Markides & Geroski, 2005). In general, disruptive innovations change habits of consumers in markets and undermine the competences and complementary assets of existing producers. Calvano (2007) argues that: "we highlight the role of destruction rather than creation in driving innovative activity. The formal

18 For studies on science, new technology and economic growth see also Cavallo *et al.,* 2014, 2014a, 2015; Coccia 2006, 2009, 2012, 2012a, 2012b, 2015a; Coccia & Finardi, 2012, 2013; Coccia & Rolfo, 2000; Coccia & Wang, 2015, 2016.

analysis shows that destructive creation unambiguously leads to higher profits whatever the innovation cost". In particular, disruptive innovations disturb the business models of incumbents that have to counter mobilize resources to sustain their competitive advantage in the presence of market change (Garud *et al.,* 2002; Markman & Waldron, 2014). In fact, new radical technologies in markets require that incumbents undertake specific R&D investments and strategic change to support competitive advantage (Christensen & Raynor, 2003; cf., Gioia & Chittipeddi, 1991; Teece *et al.,* 1997). Current R&D management of incumbents, to support innovation processes, is more and more based on network organizations to build research alliances and strategic partnerships for increasing the access to external knowledge from new firms and/or research organizations (cf., Coccia, 2016b; Nicholls-Nixon & Woo, 2003). Kapoor & Klueter (2015) argue that incumbents tend to not invest in disruptive technological regimes and maintain a competence-enhancing approach. In some industries, such as biopharmaceutical sector, current wave of research alliances and acquisitions may help incumbents to overcome this "inertia" both in the initial stage of research and in the later stage of development. Other studies show that R&D investments of innovative enterprises in pharmaceutical industry are directed towards both internal research units and strategic alliances to accelerate the drug discovery process (Coccia, 2014).

However, theoretical framework of disruptive technologies suffers of some limitations, such as the ambiguity in the definition of disruptive innovations that considers technologies but also products and business models (cf., Christensen & Raynor, 2003; Tellis, 2006). Strictly speaking, a disruptive technological innovation is fundamentally a different phenomenon from a disruptive business-model innovation. Disruptive innovations arise in different ways, have different competitive effects, and require different responses into the organizational behaviour of incumbents and entrants (Markides, 2006, p. 19). This diversity can be due to a variation in the sources of innovation, such as in some industries, users develop innovation, in other sectors, innovations are due to suppliers of related components and product manufactures (von Hippel, 1988). A vital factor in the development of innovations is also played by the coevolution of technical and institutional events (Van de Ven & Garud, 1994). The theory of disruptive technologies also seems to show some inconsistencies in many markets because new small entrants can generate new technology and innovations but their development and diffusion in markets present many economic barriers, such as within biopharmaceutical industry (Coccia, 2014; 2016). In short, the theory of disruptive technologies presents some difficulties to explain the general drivers of technological and economic change.

This study here suggests the vital role of specific firms, called disruptive firms that in the ecosystems can generate and spread new technologies with market shifts within and between industries. The study proposes some characteristics of these disruptive firms that can clarify, as far as possible, a main source of innovation to explain drivers of technological change and, as a consequence, industrial, economic and social change.

The model of this study is in Figure 1. Unlike theoretical framework of disruptive innovation (Christensen, 1997), the theoretical framework here suggests that, leading firms -called disruptive firms-support the emergence and diffusion of new technology and radical innovations that generate market shifts, technological and economic change.

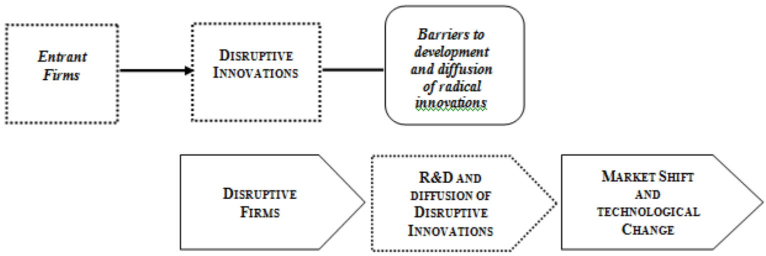


**Figure 1.** *Disruptive firms sustain technological and economic change with the introduction and diffusion of technical breakthroughs.*

The purpose of the present study is to see whether case study research supports the hypothesis that one of the general sources of technological change is due to disruptive firms (subjects) that generate market shifts, rather than disruptive technologies (objects) per se.

## Methods: case study research

The methodology is based on an inductive analysis of case study research (Eisenhardt, 1989; Eisenhardt & Graebner, 2007).

The study analyzes the managerial and organizational behavior of specific leading enterprises (disruptive firms) to explain one of the general sources of technological and economic change. The firms under study are:

* Apple Inc. for Information and Communication Technologies (ICTs)

* AstraZeneca for biopharmaceutical industry

In particular, the hypothesis of this study is that specific and distinct firms, called disruptive firms, are the driving force of market shift in industries by introducing new products, standard and/or components in markets with new technology and innovation, generating technological and socioeconomic change. Of course, the emergence of a disruptive technology is a necessary but not sufficient condition for the development and diffusion of new technology in markets that generate industrial change. Manifold factors also create important conditions for supporting technical breakthroughs. This study here focuses on specific subjects, the disruptive firms that play a vital role in competitive markets. In order to support the theoretical framework, firstly, the study analyzes shortly these firms and then we contextualized the theory with some examples of new technology and the organizational and managerial behavior of disruptive firms that generate market shift, technological and economic change.

## Inductive analysis

Apple Inc. is an American multinational technology company headquartered in California (USA) that designs, develops, and sells consumer electronics, computer software, and online services. Apple was founded in 1976 to develop and sell personal computers. It was incorporated as Apple Computer Inc. in 1977, and was renamed as Apple Inc. in 2007 to reflect its shifted focus toward consumer electronics (Wozniak, 2007). Number of employees as of October 2016 is about 116,000 units.

Apple Inc. is a disruptive firm of storage devices. A simple storage device was the floppy disk: a disk storage medium composed of a disk of thin and flexible magnetic storage medium encased in a rectangular plastic carrier. In 1983 Sony introduced 90 mm micro diskettes (better known as 3.5-inch -89 mm- floppy disks), which it had developed at a time when there were 4" floppy disks, and a lot of variations from different companies, to replace on-going 5.25" floppy disks. Apple Computer, a market leader in ICTs, decided to use in 1984 the 3½-inch drives produced by Sony in the Macintosh 128K model. This firm strategy effectively makes the 3½-inch drive a de-facto standard in markets. This Apples' decision generated a main market shift and the format 3.5" floppy disks became dominant. Floppy disks 3.5" remained a popular medium for nearly 40 years, but their use was declining by the mid-1990s (Mee & Daniel, 1996). In 1998, Apple Inc. released the iMac G3 with a new store device, called USB because it considered the floppy disk an old technology. USB—or Universal

Serial Bus—is a protocol for connecting peripherals to a computer. The development of the first USB technology began in 1994 by Intel and the USB-IF (USB Implementers Forum, Inc., formed with industry leaders like Intel, Microsoft, Compaq, LSI, Apple and Hewlett-Packard). USB was designed to standardize the connection of computer peripherals (Cunningham, 2014). The USB 1.0 debuted in late 1995 and transferred data at a rate of 12 megabits per second. This parasitic technology is associated to other host technologies, such as PCs. Interaction between these high-tech devices and a host computer without the need to disconnect or restart the computer also enables USB technology to render more efficient operation. As just mentioned, in 1998, the iMac G3 was the first consumer computer to discontinue legacy ports (serial and parallel) in favor of USB. This implementation helped to pave the way for a market of solely USB peripherals rather than those using other ports for devices. The combination of the ease of use, self-powering capabilities and technical specifications offered by USB technology and related devices helped this new technology to triumph over other port options (Au Yong, 2006; Tham, 2011). This decision of Apple generated a market shift and industrial change. In the presence of this technological change generated by a market leader, the ICT industry's reaction is to follow Apple's technological pathway, such as Dell, Hewlett-Packard, etc. that dumped the floppy drivers from their standard PCs. Trek Technology and IBM began selling the first USB flash drives commercially in 2000. IBM's USB flash drive had a storage capacity of 8 MB, more than five times the capacity of the then-common 3½-inch floppy disks (of 1440 KB). Similar pathway is with the Compact Disc (CD), a digital optical disc data storage format released in 1982 and co-developed by Philips and Sony (BBC News, 2007). The format was originally developed to store and play only sound recordings but was later adapted for storage of data (CD-ROM). Apple Inc. released the third generation of MacBook Pro in 2012 with a 15-inch screen that was a quarter thinner than its predecessor and the Retina Display with a much higher screen resolution. The MacBook Pro with Retina Display does not have an optical drive and to play discs, it is necessary to have an external Super Drive. This decision of a market leader generated a further market shift and industrial change towards new storage devices with the USB port, micro-USB or USBType-C (Hruska, 2015; Mee & Daniel, 1996; Goda & Kitsuregawa, 2012, USB, 2005).

Apple Inc. is also a disruptive firm of wired headphones. Headphones are pair of small listening devices that are electroacoustic transducers, which convert an electrical signal to a corresponding sound in the user's ear. They are designed to allow a single user to listen to an audio source privately. Firstly, the headphone with jack was created in the period 1890-1910 and with several generations is still used in many electronic devices. The study here focuses on a critical period associated to Bluetooth technology (a wireless technology standard for exchanging data over short distances from fixed and mobile devices, and building personal area networks-PANs). In fact, the revolution of ICT has generated several innovations such as the Bluetooth technology in 1999 (Bluetooth, 2017). The evolution of this technology has generated in 2004 the Bluetooth 2.0 with an Enhanced Data Rate for faster data transfer, in 2010 Bluetooth 4.0 with low energy and so on (Bluetooth, 2017). The interaction between Bluetooth and mobile phone has generated in 2002 the first mobile phone with integrated Bluetooth by Nokia, whereas the interaction between Bluetooth and headphones has also generated in 2003 the first Nokia headset, which was sold to end-users (Windows, 2012). The 29 June, 2007 Apple Inc. launched the 1st generation of iPhone with Bluetooth 2.0; the diffusion of the iPhone worldwide plays a main role in the evolution of several ICTs, driven by Apple Inc., which is one of the market leaders in smartphones and other mobile devices. In 2011, Apple Inc. has announced that new iPhone 4S supports Bluetooth 4.0 with low energy phone. In September 2016, the iPhone 7 of Generation 10th is launched without headphone jack 3.5mm. This strategic decision by Apple Inc. has a main impact for the evolution of new generations of headphones that will be more and more wireless to function, interact and survive with mobile devices (Coccia, 2017a). This decision of Apple Inc. to produce a new iPhone 7 without jack 3.5mm for headphone generates a selection pressure on manufacturers of these technologies that are focusing on new technological directions of headphones with Bluetooth™ technology (wireless) generating an on-going technological substitution and "Destructive creation" (Calvano, 2007) of current headphones with wire. In short, this case study seems to confirm that new technologies and technological trajectories are driven by specific firms that play a role of destruction of current technologies in favor of the creation of new technology and technological standards. Other examples of the organizational behavior of Apple Inc. as disruptive firm, are the destruction of the physical keyboard in smartphones with the creation of virtual keyboards in the iPhone of 1st generation in 2007. In general, disruptive firms have the market power to support new technological trajectories and industrial change. In short, the innovative behavior of market leaders can be a main driving force of technological, industrial and economic change. Moreover, market shifts are due to leader firms of host technologies, such as PC or smartphones, rather than leader firms of parasitic technologies, such as headphones, storage devices, etc. (cf., Coccia, 2017a).

AstraZeneca (AZ) is a British–Swedish research-based biopharmaceutical company. It is originated by a merger in 1999 of the Astra AB company formed in 1913 (Sweden) and British Zeneca Group formed in 1993. AstraZeneca (AZ) is a large corporation that has a net income of US$3.406 billion (AstraZeneca, 2016), total assets for US$60.12 billion (Forbes, 2016) and total number of employees for about 50,000 (AstraZeneca, 2015). The human and economic resources invested in R&D by AstraZeneca are about 15,000 units of personnel and over US$4 billion in eight countries (AstraZeneca, 2015). One of the research fields of AZ is anticancer treatments, such as for lung cancer. The current therapeutic treatments (technology) for advanced non-small cell lung cancer (NSCLC) are again mainly based on chemotherapy agents. However, this technology has low efficacy for lung cancer treatment since the mortality rate is still high (Coccia, 2014). AstraZeneca as incumbent firm in drug discovery industry has generated a main radical innovation to treat lung cancer: the target therapy Iressa® that is based on the blocking agent Gefitinib. These path-breaking anticancer drugs are generating a revolution in therapeutic treatments of lung cancer with mutation Epidermal Growth Factor Receptor (EGFR) because they block specific enzymes and growth factor receptors involved in cancer cell proliferation (Coccia, 2012, 2014, 2016). Studies in the biology show that lung cancer can become resistant to these new drugs because of a secondary mutation (T790M) that generates a progression of the cancer with several metastases and, as a consequence, high mortality within five years (Coccia, 2012). Clovis Oncology is a small pharmaceutical company, which is generating innovative products for new treatments in oncology. Clovis was founded in 2009 and is headquartered in Boulder, Colorado. This small pharmaceutical firm, Clovis oncology, has generated a new technology to treat lung cancer with mutation T790M: a new target therapy for EGFR-mutant lung cancer (Clovis Oncology, 2015). However, this small firm has difficulties in the development of this radical innovation in a sector with high capital intensity for R&D. This problem has induced Clovis oncology to enter in the stock exchange to gather financial resources directed to support R&D of several innovative products in its pipeline. The structure of the sector based on larger corporation has induced the biopharmaceutical company AstraZeneca (2015) to introduce a similar innovation for mutant lung cancers, called Tagrisso™ (AZD9291), that it was approved by US Food and Drug Administration in 2015 (AstraZeneca, 2016). This case study also confirms the vital role of large and leader firms, in competitive markets based on high intensity of R&D, that have the power to generate and/or to spread path-breaking innovations in order to achieve and sustain competitive advantage, as well as the goal of a (temporary) profit monopoly to support their market shares and industrial leadership.

Next section endeavors to detect the general characteristics of these disruptive firms that generate technological, industrial and economic change.

## Discussion

A main goal of this study is the concept of disruptive firms: they are firms with market leadership that deliberate introduce new and improved generations of durable goods that destroy, directly or indirectly, similar products present in markets in order to support their competitive advantage and/or market leadership (cf., Calvano, 2017). These disruptive firms support technological and industrial change and induce consumers to repeat their purchase in order to adapt to new socioeconomic environment. Firm strategy of these leading firms is directed to support innovation and market leadership with new technology. An example of disruptive firms is Apple Inc. that has the following organizational behaviour (cf., Backer, 2013; Barney, 1986; Fogliasso & Williams, 2014; Heracleous, 2013; O'Reilly *et al.*, 1991; Schein, 2010).

1- A main and central leader in the organization, represented in the past by the founder Steve Jobs and subsequently by the CEO Tim Cook (Apple Inc., 2017). The hierarchy in Apple's organizational structure supports strong control over the organization that empowers top leader to control everything in the organization. This organizational behavior generates limited flexibility of lower levels of the hierarchy to respond to custom needs and market demand but it provides a clear leadership for R&D and strategic management of innovative products.

2- A large market share in mobile technology and associated industrial leadership. Samsung is the largest vendor in smartphones but it only captured 14% of smartphone profits, while Apple Inc. gathered 91% of them in 2015. Apple holds nearly 45% of the U.S. OEM (Original Equipment Manufacturer) market, and in a distant second is Samsung Electronics with 28% of the market. Notably, Apple is one of the only companies to actually advance its market share (from October through January), from 42.3% to 44.6%, for a 2.3% gain. Samsung's market share declined 2% from 30% in late 2016. Apple's iPhone accounted for 34% of all smartphone activations in the U.S. last quarter, leading all other smartphone brands. Samsung was just behind the iPhone at 33%, followed by LG at 14% share of activations (Kilhefner, 2017).

3- Founded in 1976, more than 40 years ago. The firm has a long presence and experience in the sector of computer hardware, software and electronics.

4- Headquarters is localized in a high-tech region, California, of a powerful country with socioeconomic influence on wide geoeconomic areas.

5- Apple's organizational culture is also highly innovative to support firm's product development processes and firm's industry leadership. Creativity and excellence are especially important in Apple's rapid innovation processes. Moreover, secrecy is part of the company's strategy to minimize theft of proprietary information or intellectual property. Apple employees agree to this organizational culture of secrecy, which is reflected in the firm's policies, rules and employment contracts. This aspect of Apple's organizational culture helps protect the business from corporate espionage and the negative effects of employee poaching. These characteristics of the company's organizational culture are key factors that enable success and competitive advantage (cf. also, Csaszar, 2013; Damanpour & Aravind, 2012, Lehman & Haslam, 2013).

Some characteristics of the organizational behavior of AstraZeneca (AZ) are (Coccia, 2014a, 2015, 2016a):

1- A characteristic similar to previous firm is a long experience in the market and leadership position in specific segments of the biopharmaceutical sector. In fact, Astra AB formed in 1913 (Sweden) and British Zeneca Group formed in 1993. Moreover, AstraZeneca is a large corporation in industry.

2- Higher specialization of technological capability in new research fields of genetics, genomics and proteomics to support drug discovery process.

3- Another characteristic of AZ is a division of scientific labour (cf. 'division of innovative labour' by Arora & Gambardella 1995; Coccia, 2014a). R&D strategy of this incumbent firm is to create strategic alliances with emerging firms for a division of scientific labour directed to reinforce and accelerate discovery process. In fact, AZ has strategic partnerships with organizations to complement in-house technological and scientific capabilities. In this manner, AZ supports rational modes of drug discoveries by integrative capabilities developed in collaboration with biotechnology firms (cf., Coccia, 2016b; Henderson 1994, pp. 607ff; Paruchuri & Eisenman, 2012). In particular, AZ builds and reinforces the scientific capabilities by strategic alliances with external sources of innovation: i.e., partnership with academic institutions, biotechs and other pharmaceutical companies to share skills, knowledge and resources through all phases of R&D process. In addition, the acquisition of the biotechnology firm MedImmune has improved and enlarged the R&D function and technological capabilities (AstraZeneca, 2015). This R&D management of AZ organizes the R&D labs with a network structure based on strategic alliances for supporting the process of disruptive innovations (figure 2). Network R&D organization reinforces the integrative capabilities in scientific fields, collective and cumulative learning between in-house R&D and external sources of innovation. Moreover, network structure of R&D generates a multiplicity of scientific stimuli and the adoption of different and complementary R&D management approaches (cf., Coccia, 2014a, 2016b; Henderson, 1994; Jenkins, 2010).

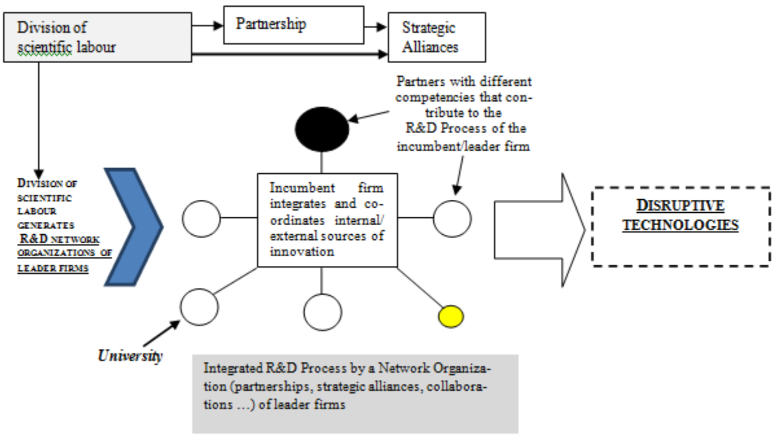


**Figure 2.** *Network of R&D function of disruptive firms to support new technologies in innovative industries.*

*Generalization of characteristics of disruptive firms that generate technological and industrial change*

The industrial dynamics shows that the theory of disruptive technology seems to be not consistent for explaining the R&D and diffusion of major innovations in main sectors such as ICTs and biopharmaceuticals. The inductive study here suggests that patterns of technological innovations in markets are dominated by incumbents rather than entrant firms, which have not the market power and structure to support path-breaking innovations across markets (Coccia, 2014a, 2015, 2016b, Daidj, 2016; Liao, 2011). In short, this study proposes the shift of the locus of one of basic causes of technological change, from disruptive technologies to disruptive firms that support path-breaking innovations and market shifts.

The case study research here reveals some general characteristics of disruptive firms that generate technological change. In particular,

1- Large size, associated to a strong market power that supports an industrial leadership.

2- Disruptive firms can or cannot generate radical and/or incremental innovations but they have the market power to spread and support new technology in markets generating industrial change.

3- Forward-looking executives seeking to pioneer radical innovations in competitive markets.

4- High R&D investments to lead the markets towards new technological trajectories, sustain competitive advantage, the goal of a (temporary) profit monopoly and industrial leadership.

5- A long historical presence and expertise in the industry for many years (e.g., more than 40 years). The historical development path in industries supports the accumulation of technological knowledge, technical expertise and experience in the sector, more and more important for R&D and strategic management.

6- Organizational and managerial behavior based on competence-destroying and competence-enhancing.

7- Strong dynamic capabilities based on combinations of competences and resources that can be developed, deployed, and protected in order to stress exploiting existing internal and external firm specific competences and to address changing environments.

8- R&D organization of disruptive firms is more and more based on a division of scientific labour. Network R&D organizations reinforce integrative capabilities, collective and cumulative learning between in-house R&D and external sources of innovation. Moreover, strategic alliances and partnership with innovative firms, university labs and suppliers support learning processes, accumulation of new knowledge and acceleration of innovation processes.

## Concluding observations

The theoretical framework of disruptive technologies seems that does not explain the dynamics of technological and economic change (cf., Christensen, 1997). The study here endeavors to clarify, whenever possible, one of driving forces of technological change based on the role of leader firms, called disruptive firms. The central contribution of this work is an approach that integrates current frameworks in management and industrial organization to explain the sources of industrial and technological change (Cooper 1990; Dosi, 1988; O'Reilly III & Tushman, 2004; 2008).

In general, firms have goals, such as achieve and sustain competitive advantage (Teece *et al.,* 1997).

One of the main organizational drivers of disruptive firms is the incentive to find and/or to introduce innovative solutions in new products, using new technology, in order to reduce costs, achieve and support the goal of a (temporary) profit monopoly and market (industrial) leadership. Case study research here also shows that R&D management of leading firms has more and more a division of scientific labour directed to accelerate innovation process and develop new technology. Disruptive firms generate significant shifts in markets with an ambidexterity strategy based on competence-destroying and competence-enhancing (cf., Danneels, 2006; Henderson, 2006; Hill & Rothaermel, 2003; Tushman & Anderson, 1986). Moreover, a main role in disruptive firms is also played by "forward-looking executives seeking to pioneer radical or disruptive innovations while pursuing incremental gains" (O'Reilly III & Tushman, 2004, p. 76). In general, disruptive firms, generating path-breaking innovations, grow more rapidly than other ones (Tushman & Anderson, 1986, p. 439).

On the basis of the argument presented in this paper, based on a case study research, we can therefore conclude that one of principal sources of technological and economic change is due to leading subjects, disruptive firms, which can be the distal sources of disruptive innovations in competitive markets, ceteris paribus. Disruptive firms have specific dynamic capabilities that generate learning processes, a vital cumulative change and path dependence in innovative industries (cf., Garud *et al.,* 2010; Teece *et al.,* 1997).

The results of the analysis here are that:

The conceptual framework here assigns a central role to leading firms (subjects) –disruptive firms- rather than disruptive technologies (objects) to sustain technological and economic change.

Disruptive firms are firms with market leadership that deliberate introduce new and improved generations of durable goods that destroy, directly or indirectly, similar products present in markets in order to support their competitive advantage and/or market leadership. These disruptive firms support technological and industrial change and induce consumers to buy new products to adapt to new socioeconomic environment.

The establishment and diffusion of disruptive technologies in markets are mainly driven by incumbent (large) firms with a strong market power. However, small (entrant) firms can generate radical innovations but they have to cope with high economic resources needed for developing new technology (cf., Caner *et al.,* 2016). This financial issue explains the strategic alliances and partnerships between some incumbent and entrant firms to develop disruptive technologies. These collaborations mark a new phase in business development of innovations.

Finally, the conceptual framework here also shows that R&D management of disruptive firms is more and more based on a division of scientific labor directed to reinforcing the integrative capabilities and collective learning between internal and external sources of innovation in order to accelerate discovery process.

Overall, then, the conceptual framework here, has several components of generalization that could easily be extended to explain the source of technological and economic change. To conclude, this study suggests that one of principal sources of industrial change is due to disruptive firms in competitive markets. To put it differently, this study provides a preliminary analysis of driving forces of technological change based on disruptive firms rather than disruptive technologies per se. However, the conclusions of this study are of course tentative. Most of the focus here is based on a case study research, clearly important but not sufficient for broader understanding of the complex and manifold sources of technological change. Moreover, the evidentiary basis of this paper is also weak, but this study may form a ground work for development of more sophisticated theoretical and empirical analyses to explain, whenever possible general causes of the technological and economic change. Hence, there is need for much more detailed research to explain the reasons for technological change in industries because we know that, in competitive markets with market dynamism, other things are often not equal over time and space. In fact, Wright (1997, p. 1562) properly claims: "In the world of technological change, bounded rationality is the rule".

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# 11. Measurement and assessment of the evolution of technology with a simple biological model

## Introduction

The measurement of technology and innovation is an increasing challenge faced by agencies, scholars, public research labs and governments for supporting technological forecasting in society (cf., Daim *et al.,* 2018; Hall & Jaffe, 2018; Linstone, 2004). Patterns of technological innovation have been analyzed using many analogies with biological phenomena (Basalla, 1988; Farrell, 1993; Nelson & Winter, 1982; Sahal, 1981; Solé *et al.,* 2013; Wagner, 2011; Ziman, 2000). Wagner & Rosen (2014) argue that the application of evolutionary biology to different research fields has reduced the distance between life sciences and social sciences, generating new approaches, such as the evolutionary theory of economic change (Nelson & Winter, 1982; cf., Dosi, 1988). In the research field of technical change and technological forecasting, the measurement of technological advances is a central and enduring research theme to explain the dynamics of the evolution of technology and technological progress (Coccia, 2005, 2005a). Scholars in these research topics endeavourof measuring technological advances, the level of technological development and changes in technology with different approaches directed to technological forecasting and assessing the impact of new technology on socioeconomic systems (Coccia, 2005; Daim *et al.,* 2018; Dodson, 1985; Faust, 1990; Fisher & Pry, 1971; Farrell, 1993; Knight, 1985; Martino, 1985; Sahal, 1981; Wang *et al.,* 2016). However, a technometrics that measures and assesses the comprehensive evolution of technology as a complex system of technologies is, at author's knowledge, unknown.

This study confronts this problem by proposing a theory of measurement of the evolution of technology based on interaction between technologies that may be useful for bringing a new perspective to explain and predict, whenever possible, the long-run coevolution between technologies. In order to position this paper in existing frameworks, the study here starts by establishing a theoretical framework of different approaches for measuring technological advances. Moreover, in broad analogy with biology, a conceptual framework of technological evolution, based on the approach of technological parasitism, is suggested (cf., Coccia & Watts, 2018). Then, the evolution of technology is modelledin simple way in terms of morphological changes between a host technology and its technological subsystems. Thecoefficient of evolutionary growth of the proposed model is quantified in real technologies using historical data. Overall, then, the technometrics here seems to be appropriate in grasping the typology and grade of the evolution oftechnology. This approach also provides fruitful information to predict which technologies are likeliest to evolve rapidly and lays a foundation for the development of more sophisticated concepts to measure and explain the general properties of the evolution of new technology in society.

## Theoretical framework of the measurement of technological advances (Technometrics)

Measurement assigns mathematical characteristics to conceptual entities. Stevens (1959, p.19) claims that the measurement is: "the assignment of numeral to objects or events". The central issue for a theory of measurement is the status of the two basic problems: the first is the justification of the assignment of the numbers to objects or phenomena (called the representational theorem); the second is the specification of the degree to which this assignment is unique (the uniqueness theorem; cf., Suppes & Zinnes, 1963; Luce *et al.,* 1963). In the research field of technology, technometrics refers to a theoretical framework for the measurement of technology, technological advances and technological change with policy implications (Sahal, 1981). The measurement of technological advances has been performed with different approaches in engineering, scientometrics, technometrics, economics and related disciplines. This section presents some of the most important methods of technometrics, without pretending to be comprehensive (Coccia, 2005, 2005a, p. 948*ff*).

## Hedonic approach to the measurement of technology

The assumption of this approach is a positive relationship between market price of a good or service and its quality. In particular, it is assumed that a particular product can be represented by a set of characteristics and by their value; hence, the quality of the product $Q_j$ is given by:

$$Q_j = f(a_1,..., a_n, X_{1j},..., X_{2j},..., X_{kj})$$

where $a_i$ is the relative importance of the $i$-th characteristics and $X_{ij}$ is the qualitative level of the same characteristics in product $j$. Technological progress can be defined here as the change in quality during a given period of time:

$$TC_j = \frac{\Delta Q_j}{\Delta t}$$

The observed changes in the price of a product can be decomposed into a "quality/technological change" effect and "pure price effect" (cf., Coccia, 2005a, pp.948-949; Saviotti, 1985).

## RAND approach to the measurement of technology

A technological device has many technical parameters that measure its characteristics and characterize the state-of-the-art (SOA). Many approaches measure the SOA and advances in SOA. Dodson (1985) considers the SOA as a convex surface in an $N$-dimensional space, where $N$ is the number of essential characteristics of a technology. He proposes the use of either a planar or an ellipsoidal surface:

*Planar*

$$\sum_{i=1}^{n}\left(\frac{x_i}{a_i}\right) = 1$$

*Ellipsoidal*

$$\sum_{i=1}^{n}\left(\frac{x_i}{a_i}\right)^2 = 1$$

Where $x_i$ is the $i$-th technological characteristic and $a_i$ is the $i$-thparameter (a constant). Alexander & Nelson (1973) developed an alternative procedure, using hyperplanes instead of ellipses.Overall, then, the hedonic and the RAND techniques for measuring technological advances are very similar and differ only in their choice of the dependent variable, which is price in the former and calendar year in the latter (Coccia, 2005a, pp.949-952).

## Functional and structural measurement of technology

The technique by Knight (1985) is based on a functional and a structural description of a given technology over time to detectits evolution. The structural model was originated by Burks *et al.,* (1946) that describe the computing system by outlining the pieces of equipment the computer must have, the purpose of devices, and the way the items interact with one another to perform as a computer. The functional description of a new computer over an earlier one indicates that technological advancement has taken place, but it does not specify the details of new development. In order to explain the technological advances, it is also necessary to use the structural descriptionby comparing the structure of new systems with that of earlier computers (cf., Coccia, 2005a, pp.955-957).

## Wholistic and holistic approaches to the measurement of technology

Sahal (1981) suggests two ideas of technometrics. In the first approach (called *Wholistic*), the state-of-the-art (SOA) is specified in terms of a surface of constant probability density given the distribution of technological characteristics. The SOA at any given point in time is represented by a probability mountain, rising above the plane. The level of technological capability is given by the height of the mountain. Instead, the magnitude of technological change can be estimated by the difference in the heights of successive mountains. In the second approach (called *Holistic*), a technological characteristic is specified as a vector in an $N$-dimensional space generated by a set of $N$ linearly independent elements, such as mass, length, and time. The length of the vector represents the magnitude of a technological characteristic, while the kind of the characteristic is represented by the direction. In this case, the SOA reduces to a point. The successive points at various times constitute a general pattern of technological evolution that evinces a series of *S*-shaped curves. These two approaches are distinct but related (Coccia, 2005a, p.955).

## Seismic approach to the measurement of technology

This approach, elaborated by Coccia (2005), categorizes effects of technological change through a scale similar to that used in seismology by Mercalli. In particular, according to the seismic approach, innovations of higher intensity generatea series of effectson subjects and objects within and between geoeconomic systems. The intensity of innovation on socioeconomic systems is measured with an indicator called Magnitude of Technological

Change, which is similar to the magnitude of the Richter scale that measures the energy of earthquakes (cf., Coccia, 2005a, pp.967-969).

### Technological advances measured with patent data

These studies are aimed to investigate technological evolution considering the patent data. Faust (1990, p.473) argues that patent indicators allow for a differentiated observation of technological advances before the actual emergence of an innovation, such as technological development in the scientific field of superconductivity. Wang *et al.* (2016, p.537ff) investigate technological evolution using US Patent Classification (USPC) reclassification. Results suggest that:"patents with Inter-field Mobilized Codes, related to the topics of 'Data processing: measuring, calibrating, or testing' and 'Optical communications', involved broader technology topics but had a low speed of innovation. Patents with Intra-field Mobilized Codes, mostly in the Computers & Communications and Drugs & Medical fields, tended to have little novelty and a small innovative scope" (Wang *et al.,* 2016, p.537, original emphasis). Future research in this research field should extend the patent sample to subclasses or reclassified secondary USPCs in order to explain the in-depth technological evolution within a specific scientific field.

### Measuring technological evolution using a model of technological substitution

In the context of the measurement of technological advances, Fisher & Pry (1971, p.75) argue that technological evolution consists of substituting a new technology for the old one, such as the substitution of coal for wood, hydrocarbons for coal, robotics technologies for humans (see Daim *et al.,* 2018), etc. They suggest a simple model of technological substitution that contains only two parameters. Technological advances are here represented by competitive substitutions of one method of satisfying a need for another. Fisher & Pry (1971, p.88) state that: "The speed with which a substitution takes place is not a simple measure of the pace of technical advance… it is, rather a measure of the unbalance in these factors between the competitive elements of the substitution".

New approaches of technological assessment apply technology development envelope to detect multiple pathways for technological evolution and construct strategic roadmapping as illustrated by Daim *et al.,* (2018, p. 49ff) for robotics technologies.

Overall, then, although different approaches of themeasurement of technological advances are suggested (Arthur & Polak, 2006;

Sahal, 1981; Daim *et al.,* 2018), a technometrics that measures the evolution of technology considering how subsystems of technology interact with a host technology in a complex system of technology is, at author's knowledge, unknown. To reiterate, this study endeavours to measure the evolution of technologywith a new perspective based on coevolution between technologies to predict the long-term development of the whole complex system of technology.

Next section presents the conceptual framework of the technometrics here, which is based on the theory of technological parasitism (Coccia & Watts, 2018).

## A proposed technometrics for the evolution of technology in complex systems

Hodgson & Knudsen (2006) suggest a generalization of the Darwinian concepts of selection, variation and retention to explain how a complex system evolves (Hodgson 2002, p.260; cf., Levit *et al.,* 2011; Schubert, 2014, p.486ff). In economics of technical change, it is become commonplace to argue that the generalization of Darwinian principles ("Generalized Darwinism") can assist in explaining the nature of innovation processes (cf., Basalla, 1988). Sahal (1981) argues that: "evolution…pertains to the very structure and function of the object (p. 64) …involves a process of equilibrium governed by the internal dynamics of the object system (p. 69)". The process of development of technology generates the formation of a complex system (cf., Sahal, 1981, p.33). Evolution of a technology concerns a process governed by the interaction between acomplex systemof technology and its inter-related systems and subsystems (Coccia & Watts, 2018). An important step towards the measurement and assessment of technological progress is to first clarify the concept of complex system. Simon (1962, p.468) states that: "a complex system [is]… one made up of a large number of parts that interact in a nonsimple way… complexity frequently takes the form of hierarchy, and… a hierarchic system… is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem." McNerney *et al.,* (2011, p.9008) argue that: "The technology can be decomposed into $n$ components, each of which interacts with a cluster of $d$–1 other components" (cf., Andriani & Cohen, 2013; Angus & Newnham, 2013; Arthur & Polak, 2006, Barton, 2014; Gherardi & Rotondo, 2016; Kauffman & Macready, 1995; Kyriazis, 2015; McNerney *et al.,* 2011; Solé *et al.,* 2013). Arthur (2009, pp.18-19) claims that the evolution of technology is due to combinatorial evolution: "Technologies somehow must come into being as fresh combinations of what already exists". This combination of components and assemblies is organized into systems to some human purpose and has a hierarchical and recursive structure. This studyhere endeavours, starting from concepts just mentioned, to measure technological advances in a framework of host-parasite technological systems, in a broad analogy with ecology (Coccia & Watts, 2018). Basic concepts of this conceptual framework are by Coccia & Watts (2018).

Technology is defined as a complex system that is composed of more than one component and a relationship that holds between each component and at least one other element in the system. The technology is selected and adapted in the Environment *E* to satisfy needs and human desires, solve problems in human society and support human control of nature.

Interaction between technologiesin complex system is a reciprocal adaptation between technologies with interrelationship of information/resources/energy and other physical phenomena to satisfy needs and human wants.

Coevolution of technologies *is* the evolution of reciprocal adaptations in a complex system that generates innovation—i.e., a modification and/or improvement of technologies that interact and adapt in a complex system to expand content of the human life-interests whose increasing realization constitutes progress.

In general, host technologies form a complex system of parts and subsystems that interact in a non-simple way (*e.g.,* batteries and antennas in mobile devices; cf., Coccia & Watts, 2018; Coccia, 2017). In this context, Coccia (2017a) states the *theorem of impossible independence* of any technology that: in the long run, the behaviour and evolution of any technology is not independent from the behaviour and evolution of the other technologies.In fact, Sahal (1981, p.71) argues that: "the evolution of a system is subject to limits only insofar as it remains an isolated system."

Overall, then, the theory of technological parasitism (Coccia & Watts, 2018), shortly described here, proposes that the interaction between technologies in a complex system tends to generate stepwise coevolutionary processes of a whole system of technology within the "space of the possible" (Wagner & Rosen, 2014, *passim*).

In order to operationalize the approach of technological parasitism to measure and predict the evolution of technology, this study proposes a simple model of technological interaction between a host technology *H* and an interrelated subsystem *P*. This model focuses on morphological changes in subsystems of technology in relation to proportional changes in the overall host system of technology. This model, based on the biological principle of allometry, was originally developed by biologists to study the differential growth rates of the parts of a living organism's body in relation to the whole body during evolution processes (Reeve & Huxley, 1945; Sahal, 1981).

## A model of technological evolution

Let *P(t)* be the extent of technological advances of a technology *P* at the time *t* and *H(t)* be the extent of technological advances of atechnology *H* that is a master or host systemthat interacts with *P*, at the same time (cf., Sahal, 1981, pp.79-89). Suppose that both *P* and *H* e volve according to some *S*-shaped pattern of technological growth, such a pattern can be represented analytically in terms of the differential equation of the logistic function:

$$\frac{1}{H}\frac{dH}{dt}=\frac{b_1}{K_1}\left(K_1-H\right)$$

We can rewrite the equation as:

$$\frac{K_1}{H}\frac{1}{\left(K_1-H\right)}dH=b_1dt$$

The integral of this equation is:

$$\log H-\log\left(K_1-H\right)=A\ +b_1t$$

$$\log\frac{K_1-H}{H}=a_1-b_1t$$

$$H=\frac{K_1}{1+\exp\left(a_1-b_1t\right)}$$

$a_1=b_1t$ and $t$ = abscissa of the point of inflection.

The growth of $H$ can be described respectively as:

$$\log\frac{K_1-H}{H}=a_1-b_1t \tag{1}$$

*Mutatis mutandis*, for *P(t)* in similar way of *H(t),* the equation is:

$$\log\frac{K_2-P}{P}=a_2-b_2t \qquad (2)$$

The logistic curve here is a symmetrical *S*-shaped curve with a point of inflection at 0.5K with $a_1$ = constant depending on the initial conditions, $K_1$ = equilibrium level of growth, and $b_1$ = rate-of-growth parameter.

Solving equations [1] and [2] for *t*, the result is:

$$t=\frac{a_1}{b_1}-\frac{1}{b_1}\log\frac{K_1-H}{H}=\frac{a_2}{b_2}-\frac{1}{b_2}\log\frac{K_2-P}{P}$$

The expression generated is:

$$\frac{H}{K_1-H}=C_1\left(\frac{P}{K_2-P}\right)^{\frac{b_1}{b_2}} \qquad (3)$$

$C_1=exp[b_1(t_2-t_1)]$ (for $t_2$ and $t_1$ cf., eqs. [1] and [2]); when P and H are small in comparison with their final value, the simple model of technological evolution is given by:

$$P=A_1(H)^{B_1} \qquad (4)$$

where $A_1=\frac{K_2}{(K_1)^{\frac{b_2}{b_1}}}C_1$ and $B_1=\frac{b_2}{b_1}$

The logarithmic form of the equation [4] is a simple linear relationship:

$$LnP=LnA_1+B_1LnH \qquad (5)$$

$B_1$ is the evolutionary coefficient of growththat measures the evolution of technology and is quantified in real instances in the next section.

This model of the evolution of technology [5] has linear parameters that are estimated with the Ordinary Least-Squares Method. The value of $B_1$ in the model [5] measures the relative growth of $P$ in relation to the growth of H andindicates different patterns of technological evolution: $B_1<1$ (underdevelopment), $B_1\geq 1$ (growth or development of technology). In particular,

$B_1 < 1$, whether technology P (a subsystem of H) evolves at a lower relative rate of change than technology H; the whole hosttechnology H has a slowed evolution (underdevelopment) over the course of time.

$B_1$ has a unit value: $B_1 = 1$, then the two technologies P and H have proportional change during their evolution: i.e., acoevolution between a whole system of technology (H) and its interacting subsystem P. This case of the proportional change generates a technological evolution of isometry between elements of a complex system. In short, when B=1, the whole system of technology H here has a proportional evolution of its component technologies (growth) over the course of time.

$B_1 > 1$, whether P evolves at greater relative rate of change than H; this pattern denotes disproportionate technological advances in the structure of a subsystem P as a consequence of change in the overall structure of a host technological system H. The whole system of technology H has an accelerated evolution (development) over the course of time.

This technometrics justifies the representational and uniqueness theorem in the measurement of the evolution of technology. Moreover, results of model [5], represented by the coefficient of evolutionary growth of technology,can be systematized in an ordinal scale that indicates the grade and type of the evolution of technology (table 1).

**Table 1.** *Scale of the evolution of technology in complex systems*

| *Grade of evolution* | *Coefficient of evolutionary growth* | *Type of the evolution of technology* | *Associated Evolutionary stages of the evolution of technology* | *Predictions* |
|---|---|---|---|---|
| 1 Low | B<1 | Slowed | Underdevelopment | Technologyevolves slowly over the course of time |
| 2 Average | B=1 | Proportional | Growth | Technologyhas a steady-state path of evolution |
| 3 High | B>1 | Accelerated | Development | Technologyis likeliest to evolve rapidly |

Properties of the scale of the evolution of technology (Table 1) are:

Technology of higher rank-order (grade) on the scale has higher technological advances of lower rank-order (grade) technologies.

If a technology has the highest ranking on the scale (i.e., three), it evolves rapidly (development) over the course of time. Vice versa, if a technology has the lowest ranking on the scale (i.e., one), it evolvesslowly (underdevelopment).

Evolution of technology of higher rank order on the scale has accumulated all previous stages of low rank order and generatesa fruitful symbiotic growth between a whole system of technology H and its interacting subsystem-components P*i*(*i*=1, .., *n*).

# Materials and method

## Data and their sources

The evolution of technology is illustrated here using historical data of four example technologies: farm tractor technology, freight locomotive technology, generation of electricity technology in steam-powered and internal-combustion plants in the USA. Sources of data are tables published by Sahal (1981, pp.319-350, originally sourced from trade literature; cf., also Coccia, 2018). Note that data from the earliest years and also the war years are sparse for some technologies.

## Measures

Technological parameters that measure the evolution of technology are given by Functional Measures of Technology (FMT) over the course of time to take into account both major and minor innovations (cf., Sahal, 1981, pp. 27-29).

FMTs for farm tractor are:

fuel-consumption efficiency in horsepower-hours over 1920-1968 CE indicates the technological advances of engines (a subsystem) of farm tractors. This FMT represents the dependent variable P in the model [5].

mechanical efficiency (ratio of drawbar horsepower to belt or power take-off –PTO- horsepower) over 1920-1968 CE is a proxy of the technological advances of farm tractor. This FMT represents the explanatory variable H in the model [5].

For freight locomotive, FMTs are:

Tractive efforts in pound over 1904-1932 CE indicate the technological advances of locomotive. This FMT represents the dependent variable P in the model [5].

Total railroad mileage over 1904-1932 CE indicates the evolution of the infrastructure system of railroad. This FMT represents the explanatory variable in the model [5].

For steam-powered electricity-generating technology, FMTs are:

Average fuel-consumption efficiency in kilowatt-hours per pound of coal over 1920-1970 CE indicates the technological advances of boiler, turbines and electrical generator (subsystems of steam-powered plant). This FMT represents the dependent variable P in the model [5].

Average scale of plant utilization (the ratio of net production of steam-powered electrical energy in millions of kilowatt-hours to number of steam powered plants) over 1920-1970 CE indicates a proxy of the technological advances of the overall electricity-generating plants. This FMT represents the explanatory variable in the model [5].

For internal-combustion type electric power technology, FMTs are:

Average fuel-consumption efficiency in kilowatt-hours per cubic foot of gas 1920-1970 CE indicates the technological advances of boiler, turbines and electrical generator (subsystems of internal combustion plant). This FMT represents the dependent variable P in the model [5].

Average scale of plant utilization (the ratio of net production of electrical energy by internal-combustion type plants in millions of kilowatt-hours to total number of these plants) over 1920-1970 CE indicates a proxy of the technological advances of the overall electricity-generating plants with this internal-combustion technology. This FMT represents the explanatory variable in the model [5].

## Model and data analysis procedure

Model [5] of the technological evolution implemented in real instances here is:

$$Ln\ P_t = Ln\ a + B\ Ln\ H_t + u_t \qquad \text{(with } u_t\text{= error term)} \qquad (6)$$

$a$ is a constant

$P_t$ will be the extent of technological advances of technology $P$ that represents a subsystem of the Host technology $H$ at time $t$

$H_t$ will be the extent of technological advances of technology H that represents the host technology of an interacting subsystem technology $P$ at time $t$; H technology is the driving force of the evolutionary growth of overall interrelated subsystems of technology.

Thee quation of simple regression [6] is estimated usingthe Ordinary Least Squares method. Statistical analyses are performed with the Statistics Software SPSS® version 24.

## Case studies of the evolution of technology in the agriculture, rail transport and electricity generation

The evolution of technology modelled here is illustrated with realistic examples using historical data of farm tractor, freight locomotive, steam-powered electricity-generating technology and internal-combustion type electric power technology in the USA. Table 2 shows the descriptive statistics of the study.

**Table 2.** *Descriptive statistics (logarithmic scale)*

| | LN Fuel consumption efficiency in horse power hours (Engine of Tractor) | LN Mechanical efficiency ratio of drawbar horsepower to belt (Tractor efficiency) | LN Tractive efforts in pound (Locomotive power) | LN Total railroad Mileage (Infrastructure for locomotive) |
|---|---|---|---|---|
| Years | 44 | 44 | 29 | 29 |
| Mean | 2.13 | 4.19 | 10.43 | 12.86 |
| Std. Deviation | 0.27 | 0.146 | 0.22 | 0.11 |
| Skewness | -0.76 | -0.68 | -0.21 | -1.04 |
| Kurtosis | -0.83 | -0.56 | -1.19 | -0.06 |
| | LN Average fuel consumption efficiency in kwh per pound of coal (turbine and various equipment in steam-powered plants) | LN Average scale of steam-powered plants | LN Average fuel consumption efficiency in kwh per cubic feet of gas (turbine and various equipment in internal-combustion plants) | LN Average scale of internal-combustion plants |
| Years | 51 | 51 | 51 | 51 |
| Mean | -0.25 | 4.85 | -2.75 | 0.51 |
| Std. Deviation | 0.34 | 1.43 | 0.33 | 0.85 |
| Skewness | -0.67 | -0.17 | -0.67 | 0.02 |
| Kurtosis | -0.09 | -1.26 | 0.04 | -1.64 |

## Results of the evolution of farm tractor technology (1920-1968)

Table 3 shows theevolutionary coefficient of growth of farm tractor technology, from model [6], is $B$ = 1.74, i.e., $B$ >1: the subsystem component technology of engine (P) has a disproportionate technological growth in comparison with overall farm tractor (H). This coefficient indicates a high grade of the evolution of technology (three) anda development of the whole system of farm tractor technology (cf., Figure 1).

**Table 3.** *Estimated relationship for farm tractor technology*

| *Dependent variable*: LN fuel consumption efficiency in horsepower hours (technological advances of engine for tractor at $t$=1920, …, 1968) | | | | |
|---|---|---|---|---|
| | *Constant* $\alpha$ *(St. Err.)* | *Evolutionary coefficient* $\beta$=*B* *(St. Err.)* | $R^2$ *adj. (St. Err. of the Estimate)* | *F (sign.)* |
| Farm tractor | –5.14*** (0.45) | 1.74*** (0.11) | 0.85 (0.10) | 256.44 (0.001) |

**Note:** ***Coefficient β is significant at 1‰; Explanatory variable is LN mechanical efficiency ratio of drawbar horsepower to belt (technological advances of farm tractor –Host technology), $t$= (1920–1968).

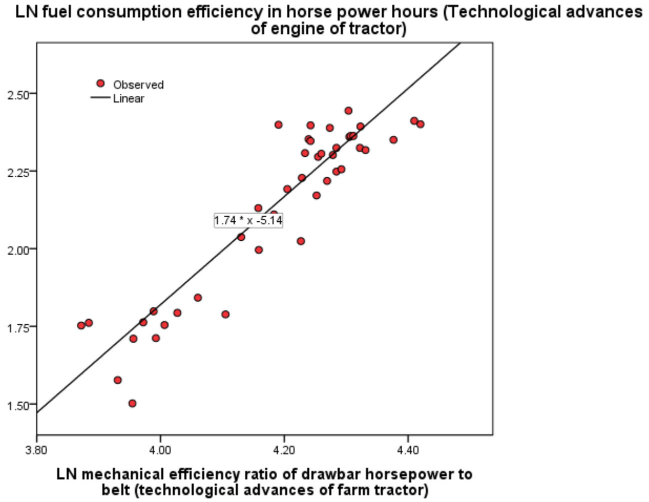


**Figure 1.** *Trend and estimated relationship of the evolution of farm tractor technology*

This result confirms the study by Sahal (1981) that the rapid evolution of farm tractor technology is due to numerous advances and radical innovations over time, such as the diesel-powered track-type tractor in 1931, low-pressure rubber tires in 1934 and the introduction of remote control in 1947 that made possible improved control of large drawn implements. The development of the continuous running power takeoff (PTO) also in 1947 allowed the tractor's clutch to be disengaged without impeding power to the implements. Moreover, itis introduced, in 1950, the 1000-rpm PTO for transmission of higher power, whereas in 1953 power steering was applied in new generations of tractor. In addition, the PTO horsepower of the tractor has more than doubled from about 27hp to 69hp over 1948-1968; finally, dual rear wheels in 1965, auxiliary front-wheel drive and four-wheel drive in 1967 have improved the overall technological performance of the tractor (Sahal, 1981, p.132ff). These radical and incremental innovations have supported the accelerated evolution of the farm tractor technology over time as confirmed by the statistical evidence here with the coefficient of evolutionary growth B>1.

## Results of the evolution of freight locomotive technology (1904–1932)

Table 4 shows that the evolutionary coefficient of freight locomotive technology is $B$ = 1.89, i.e., $B$> 1: this coefficient of growth indicates a stage of development of freight locomotive technology in the complex system of rail transportation (see, Figure 2).

**Table 4.** *Estimated relationship for freight locomotive technology*

| *Dependent variable*: LN Tractive efforts in pound of locomotive (technological advances), *t* = (1904–1932) | | | | |
|---|---|---|---|---|
| | *Constant* $\alpha$ *(St. Err.)* | *Evolutionary coefficient* $\beta$=*B* *(St. Err.)* | $R^2$ *adj.* *(St. Err. of the Estimate)* | *F* *(sign.)* |
| Farm tractor | –13.87*** (1.48) | 1.89*** (0.12) | 0.91 (0.07) | 270.15 (0.001) |

**Note:** ***Coefficient β is significant at 1‰; Explanatory variable is LN Total railroad mileage (technological advances of the infrastructure –Host technology) at *t*=1904, …, 1932

This development of freight locomotive technology can be explained with a number of technological improvements, such as the introduction of the compound engine in 1906 that improved the tractive effort (Sahal, 1981). In 1912 the first mechanical stoker to use the steam-jet overfeed system of coal distribution and the substitution of pneumatically operated power reverse gear for the hand leverhave improved locomotive power. In 1916, it is introduced the unit drawbar and radial buffer that eliminated the need for a safety chain in coupling the engine and tender together. Further technological advances are due to the adoption of cast-steel frames integral with the cylinder, the chemical treatment of the locomotive boiler water supply and the introduction of roller bearings over 1930s. In particular, these technical developments reduced the frequency of maintenance work in locomotives. Subsequently, the continuous modification of the steam locomotive with reciprocating engine has led to diesel-electric locomotive by the mid-1940s (Sahal, 1981, p.154*ff*). These technological developments have supported the accelerated evolution of freight locomotive technology over time as confirmed by the coefficient of evolutionary growth B>1 calculated above.

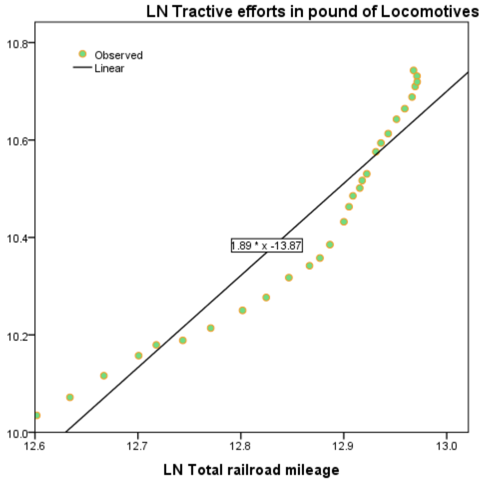


**Figure 2.** *Trend and estimated relationship of the evolution of freight locomotive technology*

## Results of the evolution of electricity generation technology (1920-1970)

Table 5 shows that steam-powered electricity-generating technology is $B = 0.23$, i.e., $B < 1$ (see alsoFigure 3).

**Table 5.** *Estimated relationship for the steam-powered electricity-generating technology (1920-1970)*

| *Dependent variable*: LN Average fuel consumption efficiency in kwh per pound of coal (technological advances of turbine and various equipment) | | | | |
|---|---|---|---|---|
| | *Constant* <br> *α* <br> *(St. Err.)* | *Evolutionary Coefficient β=B* <br> *(St. Err.)* | *$R^2$ adj.* <br> *(St. Err. of the Estimate)* | *F* <br> *(sign.)* |
| Turbine and various equipment | −1.35*** <br> (0.04) | 0.23*** <br> (0.01) | 0.93 <br> (0.09) | 675.12 <br> (0.001) |

**Note:** ***Coefficient β is significant at 1‰; Explanatory variable is Average scale of steam-powered plants (Host technology) at $t$=1920, …, 1970

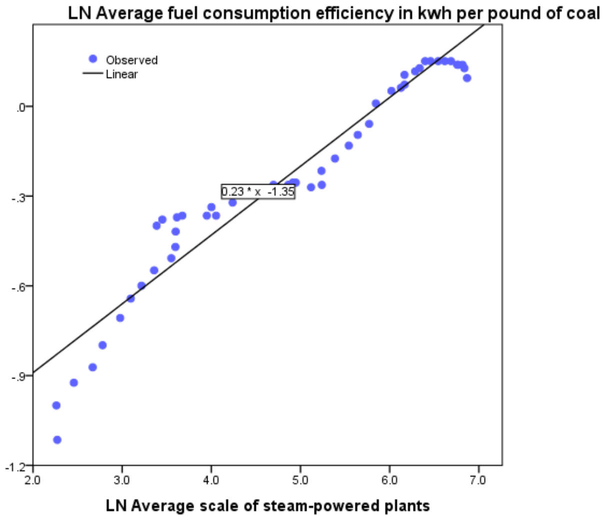


**Figure 3.** *Trend and estimated relationship of the evolution of steam-powered electricity-generating technology (1920-1970)*

Table 6 shows for internal-combustion type electric power technology similar results to steam-powered electricity-generating technology: coefficient of evolutionary growth of this technology is B = 0.35, i.e., B < 1. In short, evolution of technology in the generation of electricity both in steam-powered plants and internal-combustion plants is low and driven by an evolutionary route of underdevelopment over the course of time (see, Figure 3 and 4). This evolution of technology in the generation of electricity is associated with available natural resources, the increase in steam pressure and temperature made possible by advances in metallurgy, the use of double reheat units and improvements in the integrated system man-machine interactions to optimize the operation of overall plants (Sahal, 1981, pp.183ff)). In general, the rate of technological evolutionin the generation of technology has slowed down (underdevelopment) because of: "the deterioration in the quality of fuel and of constraints imposed by environmental conditions….other main reasons: First, increased steam temperature requires the use of more costly alloys, which in turn entail maintenance problems of their own…. Thus there has been a decrease in the maximum throttle temperature from 1200 °F in 1962, to about 1000 °F in 1970. Second, there has been lack of motivation to increase the efficiency in the use of gas in both steam-powered and internal-combustion plants because of the artificially low price of fuel due to Federal Power Commission's wellhead gas price regulation. Finally, … there has been a slowdown in generation efficiency due to heavy use of low-efficiency gas turbines necessitated by delays in the construction of nuclear power plant" (Sahal, 1981, p.184).

**Table 6.** *Estimated relationship for internal-combustion type electric power technology (1920-1970)*

| *Dependent variable*: LN Average fuel consumption efficiency in kwh per cubic feet of gas (technological advances of turbine and various equipment) | | | | |
|---|---|---|---|---|
| | *Constant* *α* *(St. Err.)* | *Evolutionary coefficient* *β=B* *(St. Err.)* | *$R^2$ adj.* *(St. Err. of the Estimate)* | *F* *(sign.)* |
| Turbine and various equipment | –2.93*** (0.02) | 0.35*** (0.02) | 0.81 (0.14) | 213.63 (0.001) |

**Note:** ***Coefficient β is significant at 1‰; Explanatory variable is LN Average scale of internal-combustion plants (Host technology) at *t*=1920, …, 1970

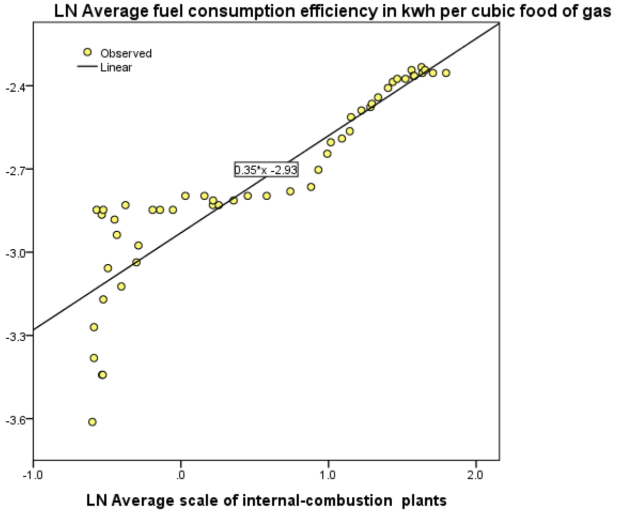


**Figure 4.** *Trend and estimated relationship of the evolution of internal-combustion type electric power technology (1920-1970)*

## Discussion

Themeasurement of technological advances needs a unifying perspective to explain and predict the evolution of technology, which has more and more complexity in markets with rapid changes. This article proposes a new perspective for the measurement of the evolution of technology that is adapted from ecology and is modelled with a simple modelof morphological change thatassessesand predicts the technological developmentdriven by interaction between a host technology and its parasitic- subsystems of technologyover the long run. As a matter of fact, some scholars argue that technologies and technological progress display numerous life-like features, suggesting a deep connection with biological evolution (Basalla, 1988; Erwin & Krakauer, 2004; Solé *et al.,* 2011; Wagner & Rosen, 2014). In general, biological evolution seems to support possible explanations of technology evolution (Basalla, 1988). In this context, this study extends the broad analogy between technological and biological evolution to more specifically focus on the potential of a technometrics based on interaction between technologies in complex systems, but fully acknowledge that interaction between technologies is not a perfect analogy of biological/ecological interaction; of course, there are differences (Ziman, 2000; Jacob, 1977; Solé *et al.,* 2013). For studying technical progress, though, the analogy with biology and ecology is a source of ideas because biological evolution has been studied in-depth and provides a logical structure of scientific inquiry in research fields concerning technology.

The study here suggestsa theoretical framework that seems to be appropriate to measure the evolution of technology and predict possible evolutionary pathways of the complex systems of technology.In particular, the evolution of technology here is based on a simple assumption that technologies are complex systems that interact in a nonsimple way with other technologies and its interrelated subsystems of technology. Thedynamics of the evolution of technology here is based on a S-shaped growth curve of technological advances both forthe whole system of technology and for its interrelated subsystem components. The approach here is formalized with a simple model that contains only two parametersand provides the coefficient of evolutionary growth, which is useful to measure the typology of evolution of technology and predict which technologies are likeliest to evolve rapidly.In particular, the technometrics here provides three simple grades of the evolution of technology according to the coefficient of evolutionary growth: $B<1$ (underdevelopment), $B=1$ (growth) and $B>1$ indicates the development of the whole system of technology. Hence, the evolution of technology is a multidimensional process of interaction within and between technologies, such that a technology, which remains an isolated system and does not interact with other technologies, can slow down technological advances over the course of time (Coccia, 2017a; Sahal, 1981). The technometrics proposed here, illustrated infour example technologies, provides consistent patterns of the evolution of technologiessupported by the history of technology.

One of the most important findings of the proposed theoretical framework here is two general properties of the accelerated evolution of technology as a complex system: (1) disproportionate growth of its subsystems and (2) increase in the complexity of the structure of technology during the rapid evolutionary growth of its interacting subsystem-component technologies.

Thequantification of the coefficient of evolutionary growth of the model [6], called B, can also suggest reliable predictions of the long-term development of technology, given by:

Evolution of technology in the form of development of the whole system is governed by a process of disproportionate growth in its subsystems (B>1) as a consequence of change in the overall system of the host technology (e.g., technological development of farm tractor and freight locomotivetechnologies described here).

Evolution of technology reduces speed when its component subsystems have low changes as a consequence of changes of the whole system of host technology (B<1), generating underdevelopmentof the whole system of technology over the course of time (e.g., the electricity generation technology).

The long-run evolution of a technology depends on the behaviour and evolution of associated technologies (interacting systems and subsystems). To put it differently, long-run evolution of a specific technology is enhanced by the integration of two or more technologies that generate co-evolution of system innovations.

Technologies having an accelerated symbiotic growth of itsinteracting subsystem technologies (B>1) advance rapidly, whereas technologies with low growth of its interacting parts (B<1) improve slowly.

Isolated system of technology, with low interaction between systems and among the parts of its system, is subject to limits of long-run evolution.

In general, this study shows that the technology is a complex system driven by manifold factors. Sahal (1981, p.69) argues that the dynamics of a system is affected by its history and associated processes of self-generating and self-constraining of its growth. Moreover, the evolution of technological system is also due to processes of learning, based on interaction processes between different technological devices and its subsystems that determine the scope for the utilization of a technology andthe directions of technological guideposts and innovation avenues over time (cf., Sahal, 1981; Nelson & Winter, 1982). In fact, Sahal (1981, p.82, original italics) argues that: "the role of learning in the *evolution* of a technique has profound implications for its *diffusion* as well". In addition, findings here show that the evolution of technologies is affected by scientific and technological advances of the whole system and its subsystems (e.g., for farm tractor and freight locomotive technologies) but it is also affected by socio-institutional environment that can slowdown technological progress (e.g., low technological advances in steam-powered electricity-generating technology and internal-combustion type electric power technology).

The finding of this study could aid technology policy and management of technology to design best practices forsupporting development of new technology, and as a consequence, industrial and economic change in human society. Proposed theory here hasalso a number of implications for the analysis of nature, sources and evolution of technology. One of the most important implications is theinteraction between technologyand its subsystem components in complex systems that drivethe evolutionary pathways of complex systems of technology and technological diversification over time and space. This suggested approach of technometrics here is consistent with the well-established literature by Arthur (2009) as well as with studies that consider structural innovations and systems innovations based on integration of two or more symbiotic technologies (Sahal, 1981).

The main limitation of this approach is in the lack of useful data in sufficient quality for different technologies. Future efforts in this research fieldrequire a substantial amount of data of technological parameters to provide additionalempirical evidence of the different pathways of technological evolutionover time and space.

To conclude, the proposed approach here based on the ecology-like interaction between technologies—may lay the foundation for development of more sophisticated concepts and theoretical frameworks in technometrics and technological forecasting. In particular, this study constitutes an initial significant step in measuring the evolution of technology considering the interaction between technologies in complex systems to predict the long-run behaviour and evolution of fruitful technological trajectories in society. Nevertheless, identifying comprehensivetechnometrics in different domains of technology, affected by manifold and complex factors, is a non-trivial exercise. Wright (1997, p. 1562) properly claims that: "In the world of technological change, bounded rationality is the rule."

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# 12. Functionality development of product innovation: An empirical analysis of the technological trajectories of smartphone

## Introduction

In the research field of technical change and technological forecasting, the analysis of technological advances is a central and enduring research theme to explain the evolution of technology and technological progress in society (Coccia, 2005, 2005a; Saviotti, 1985). In particular, the technology analysis of nature and evolution of innovation is important research field for predicting evolutionary pathways and critical characteristics of new technologies (cf., Arthur, 2009; Arthur & Polak, 2006; Hall & Jaffe, 2018; Linstone, 2004; Coccia, 2017). Scholars in these research topics endeavor of measuring technological advances, the level of technological development and changes in technology with different approaches directed to technological forecasting of emerging trajectories (Coccia, 2005; Daim *et al.,* 2018; Faust, 1990; Farrell, 1993; Sahal, 1981; Tran & Daim, 2008; Wang *et al.,* 2016). However, studies about methods for detecting the technical characteristics supporting the evolution of specific technologies are rather elusive. In this context, the study of technological advances in smartphone technology plays a vital role to explain general properties of the evolution of technology because this device is one of the most important Information and Communication Technologies (ICTs) used by people in society (Lee & Lim, 2014; Coccia, 2017a; cf., Teece *et al.,* 1997). The goal of this study is to suggest a method for technology analysis to detect and forecast the most important technical characteristics that support greater functionality development of smartphone technology in markets.

Especially, the evolution of smartphone technology is modeled here in simple way with a linear function of hedonic pricing to detect technical characteristics of these ICTs that matter most. This approach can be generalized to analyze and explain evolutionary pathways of new technology in society. In addition, results can support best practices of management of technology for guiding funding for R&D and forecasting critical technologies and/or technical characteristics of products that are likeliest to evolve rapidly in society. Before presenting the method and results of this study, next section introduces the theoretical framework.

## Theoretical framework

A smartphone or pocket-sized computer for voice, message and data communication is among the most important ICTs used by people worldwide in current society (Woods, 2018). The diffusion of mobile phones and smartphones, measured with subscribers, has growth rates higher than fixed phone (Watanabe *et al.,* 2012). Lee & Lim (2014, pp.808-809) argue that the main characteristics of mobile phones are: the mass in grams, physical dimensions in terms of length, width and thickness in mm, the measured dominant frequency of vibration in Hz, the peak acceleration measured in $m/s^2$ and peak inertia force measured in kg $m/s^2$, etc.

The evolution of smartphone technology is associated with stepwise functionality development ("the ability to dramatically improve performance of production processes, goods and services by means of innovation", Watanabe *et al.,* 2009, p.738). Watanabe *et al.* (2009, p.738) also argue that: "functionality development stimulates customer's demand leading to rapid increase in number of subscribers. This increase leads to dramatic decline in handsets prices as a result of both effects of learning and economies of scale. Balance between prices increase by functionality development and their decrease by effects of learning and economies of scale has been the driving force behind the growth in mobile phones" (cf., Lacohée *et al.,* 2003). In economics of innovation and industrial organization, scholars have investigated specific technologies, such as digital camera considering a relation between sales and characteristics of all camera models (Carranza, 2010). In particular, Carranza (2010, p. 605) argues that the functionality development of the quality of cameras is due to increasing resolution from around 0.5 in 1998 to more than 1.5 megapixels in 2001, whereas the average optical zoom of sold cameras has decreased slightly during the same period of time. This technological trade-off is explained as follows: increased resolution, which facilitates the use of a digital zoom, is a good and cheaper substitute for the optical zoom, especially among lower-quality cameras. In this context, Watanabe *et al.,* (2012) argue that learning effects in ICTs can be the sources of its self-propagating development of technology, acquiring new functionality from digital industry.

Stimulated by these studies, a fundamental problem in economics of innovation is which technological characteristics matter most in evolutionary pathways of new technology to predict fruitful technological trajectories (Coccia, 2005, 2005a, 2017). The literature of appropriate methods to explain this technological problem is rather scarce. The study confronts this question here by developing a theoretical framework based on technology as a complex systems and a hedonic pricing method, which endeavor to analyze smartphone technology to detect the most important technical characteristics driving evolutionary pathways over time.

Simon (1962, p.468) states that: "a complex system [is]… one made up of a large number of parts that interact in a nonsimple way…. complexity frequently takes the form of hierarchy, and ….a hierarchic system… is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem." McNerney *et al.,* (2011, p.9008) argue that: "The technology can be decomposed into $n$ components, each of which interacts with a cluster of $d$–1 other components" (cf., Gherardi & Rotondo, 2016). Technology here is defined as a complex system that is composed of more than one component and a relationship that holds between each component and at least one other element in the system. Sahal (1981) points out that systems innovations are due to integration of two or more symbiotic technologies.

The analysis of technological advances has been performed with different approaches in engineering, scientometrics, technometrics, economics of innovation and related disciplines (Coccia, 2005, 2005a, p.948ff). One of these methods is the hedonic approach applied to technology analysis. Hedonic methods consider both economic and technical information (Saviotti, 1985). In economics, this approach is motivated by economic goals (e.g., sources of the competitive advantage of firms), whereas in engineering focuses on specific technical changes to improve performance of new products (Triplett, 1985, 2006). The assumption of this approach is a positive relationship between market price of a good and its quality. In particular, a product can be represented by a set of characteristics and by their value. The quality of the product $Q_j$ is assumed to be a function of the defining characteristics as follows:

$$Q_j = f(a_1,\dots,a_i,\dots,a_n, X_{1j},\dots,X_{2j},\dots,X_{hj})$$

$a_i$ = relative importance of the $i$-th characteristics ($i$=1, …, n)

$X_{ij}$ =the qualitative level of the same characteristics in product $j$

Technological progress or technological evolution of the product $j$ is given by the change in quality during a period of time:

$$TC_j = TP_j = \frac{\Delta Q_j}{\Delta t}$$

The observed changes in the price of a product can be decomposed into a "quality/technological change" effect and "pure price effect" (cf., Coccia, 2005a, pp.948-949; Saviotti, 1985, p.309ff). In general, Saviotti (1985, p.315, original emphasis) argues that: "hedonic price method has been applied mostly to products. In order to apply the method to process technology, one must be able to represent individual elements of the process and the process as a whole as sets of characteristics, and cost/prices must be known for individual elements of the process. Furthermore, a sufficiently large number of 'process models' should be available to obtain statistically significant results".

The hedonic pricing method is based on specific steps to assess the evolution of technology.

Firstly, in order to analyze technological evolution of a product, it is important to detect the product characteristics ($X_{ij}$) and their relative importance ($a_i$). Product characteristics can be found in the technical literature that provides the technical characteristics of products (i.e., those characteristics describing internal aspects of technology). Technical characteristics are manipulated by engineers in order to support innovative devices over time. Saviotti (1985, p.310) shows the example of the bore, stroke, number of revolutions per minute (RPM) of a motor car engine that are manipulated to supply the required engine power, fuel consumption, etc. Carranza (2010) has showed with a hedonic price model that camera prices decreased over time, controlling for the improving quality, measured with technical characteristics of resolution and digital zoom. This approach is important in markets because adopters of a technology are interested to technical characteristics supplied by a product to fulfil their needs.

Secondly, method of hedonic pricing requires the selection of a set of variables given by technical characteristics of a product.

Thirdly, the evolution of technology, after the identification of technical characteristics of a given product, is analyzed with a functional form for the relationship between quality and product characteristics. This functional form has to show that positive increments in technical characteristics levels must lead to an increase in quality. The simplest form of functional relationships between quality and product characteristics is a linear combination. However, the relationship between price and technical characteristics of a product is not necessarily linear, it can be semilog or log-log function (cf., Triplett, 1985). The choice between different functional forms of the hedonic pricing relationship is essentially an empirical problem (cf., Saviotti, 1985). In a log-log model of hedonic pricing, product prices are regressed with respect to technical characteristics, according to following equation:

$$logP_j = \alpha_0 + \alpha_1 logX_{1t} + \cdots + \alpha_i logX_{it} + \cdots + \alpha_n logX_{nt}$$

where

$P_j$= price of a product over time. It represents the value that firm has given to a specific product

$X_i$=explanatory variables are given by technical characteristics of product over time, such as weight, efficiency, velocity, etc.

$a_0$= constant

$a_i$= coefficient of regression (*i=1, …, n*)

This approach can explain the functionality development dynamism of technology for detecting technological trajectories directed to achieve and sustain competitive advantage of firms in markets with rapid change and fulfill needs of adopters. Next section presents the methods and materials applied here to analyze the evolution of smartphone technology.

## Materials and method

This study focuses on functionality development of smartphone technology. The crux of the study here is the measurement of the evolution of technology. A brief background of the concept of evolution is useful to clarify this study. Evolution is the stepwise and comprehensive development [it derives from Latin *evolution* –*onis,* der. of *evolvěre* = act of carrying out (the papyrus)]. In particular, the evolution of technology is due to major innovations, made possible by numerous minor innovations (Sahal, 1981, p.37). The process of development of technology generates the formation of a complex system (cf., Sahal, 1981, p.33). Sahal (1981) argues that: "evolution…pertains to the verystructure and function of the object (p.64)….involves a process of equilibrium governed by the internal dynamics of the object system (p.69)". Moreover, the short-term evolution of technology is due to changes within the system, whereas the long-term evolution is possible by forming an integrated system, the formation of increasingly comprehensive systems (Sahal, 1981, pp.73-74). In general, "the evolution of a technology often proceeds along more than one pathway so as to meet the requirements of its task environment" (Sahal, 1981, p.116). In short, evolution of technology is a constant process based on different technical and socioeconomic factors that generate a stepwise transition of technology from simple to a complex system. Using a Generalized Darwinism perspective (Hodgson & Knudsen, 2006, 2008), the evolution of technology, with the principle of selection of fruitful technical and economic characteristics, ensures diffusion and survival of successful technologies in markets (environment of technology).

The approach is modelled with a function of hedonic pricing to detect technical characteristics that matter most in evolutionary pathways over time.

## Data and their sources

Smartphone is one of the most important ICTs used by people worldwide. The market of smartphone is concentrated at the brand level, with a small number of firms having a disproportionately large market share, creating an oligopoly (Lee & Lim, 2014). Sources of data here are originally sourced from trade literature (Punto & Cellulare, 2018). In particular, this study considers a sample of *N*=738 models of smartphone from 2008 to 2018 sold in Italy during the years 2012 and 2018 by famous brands: Apple. ASUS, HTC, Huawei, LG Electronics, Motorola, Nokia, Samsung, Sony, ZTE. Table 1 shows, in detail, the composition of the sample per brands of smartphone under study.

**Table 1.** *Sample of this study*

| Brand of smartphone | N |
|---|---|
| APPLE | 16 |
| ASUS | 46 |
| HTC | 81 |
| Huawei | 121 |
| LG | 64 |
| MOTOROLA | 61 |
| NOOKIA | 112 |
| SAMSUNG | 105 |
| SONY | 80 |
| ZTE | 52 |
| Total cases (sample) | 738 |

## Measures

Firstly, this approach considers the monetary value of smartphones, which is expressed with the utilitarian unit of price in markets:

– Price *P* of smartphones (current Euros) sold in Italy during the years 2012 and 2018, though some models are launched in previous years.

Secondly, the evolution of technology here is measured with Functional Measures of Technological characteristics (FMT) in smartphone technology over 2008-2018 period to take into account both major and minor innovations (cf., Sahal, 1981, pp.27-29). FMTs in smartphone used here are given by:

– Display in inches
– Display resolution in total pixels= display size row × display size column
– Main Camera (megapixel, Mpx)
– Second Camera (megapixel, Mpx)
– Processor GHz (Giga Hertz, GHz)
– Memory Gb (Giga byte, Gb)
– RAM Gb
– Battery (milliampere hour, mAh).

## Models and data analysis procedure

The technical characteristics of smartphone have accelerated from 2006 in line with the market of ICTs (cf., Lee & Lim, 2014). In order to detect the technological trajectories of the evolution of smartphone, a preliminary analysis is performed with the arithmetic, geometric and exponential rates of growth per each vital characteristic *i* under study (*i*=1, …, *n*).

Let

FMT*i, 2018*= level of technical characteristic *i* in 2018

FMT*i, 2008*= level of technical characteristic *i* in 2008

 If the development of technical characteristic *i* (*i*=1, …, *n*) in smartphone is assumed to be of *arithmetic type*, the rate of growth is given by:

$$FMT_{i,2018} = FMT_{i,2008} + FMT_{i,2008}(r_{art} \cdot t)$$
$$FMT_{i,2018} - FMT_{i,2008} = FMT_{i,2008}(r_{art} \cdot t)$$
$$r_{art} = \frac{FMT_{i,2018} - FMT_{i,2008}}{FMT_{i,2008} \cdot t}$$

□ If the development of technical characteristic $i$ ($i$=1, …, $n$) in smartphone is assumed to be of *geometric type*, the rate of growth is given by:

$$FMT_{i,2018} = FMT_{i,2008} \cdot \left(1 + r_{geom}\right)^{t}$$

$$Log\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right) = t \cdot Log \quad \cdot \left(1 + r_{geom}\right)$$

$$Log\ \frac{\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right)}{t} = Log \quad \cdot \left(1 + r_{geom}\right)$$

$$r_{geom} = \frac{\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right)}{t} - 1 \quad \cdot$$

□ If the development of technical characteristic i (i=1, …, n) in smartphone is of *exponential type*, the exponential rate of growth is given by:

$$FMT_{i,2018} = FMT_{i,2008}\, e^{r exp_{\,i} t}$$

$$\frac{FMT_{i,2018}}{FMT_{i,2008}} = e^{r exp_{\,i} \quad t}$$

$$log\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right) = r_{exp\ i}\, t$$

$r_{exp\ i} = \frac{log\left(\frac{FMT_{\ i,2018}}{FMT_{\ i,2008}}\right)}{t}$ = rate of exponential growth of technological characteristic *i*. In order to operationalize the approach of hedonic pricing to analyze the drivers of the evolution of smartphone technology, this study considers a log-log model of hedonic pricing, in which smartphone prices are regressed with respect to technological characteristics. The specification of *log-log* model (considering data in natural logarithms) is the following equation:

$$log\ P_{smartp\ hone} = \alpha_0 + \alpha_1 log\ Display\ in\ inch \quad + \cdots + \alpha_i log\ Camera\ (megapixel) + \cdots + \alpha_n logRAM\ Gb \qquad (1)$$

$a_0$= constant

$a_i$= coefficient of regression ($i$=1, …, $n$)

A $t$-test is performed for each coefficient in the hedonic price equation. Standardized values of the coefficients of regression $a_i$

provide information about the most important technological trajectories driving the technological progress of a given product over time. This study also applies the multiple regression analysis of model (1) using the stepwise method (Criteria: Probability-of-*F*-to-enter <= .050, Probability-of-*F*-to-remove >= .100). Moreover, in order to check the generalizability of results, the study applies the hierarchical regression, considering a linear model similar to Eq. [1], to show if additional variables of interest explain a statistically significant amount of variance in dependent variable (Price of smartphone), after accounting for all other variables. This technique determines whether added variables show a significant improvement in $R^2$ (the proportion of explained variance in dependent variable by the model).

Logical models of hierarchical regression here are:

- Model 1 includes as explanatory variables, technical characteristics of smartphone that interact with visual perception of adopters, such as display resolution in pixels and camera in megapixels.
- Model 2 includes, in addition to model 1, a variable measuring the technical characteristic of storage and functionality of smartphone: RAM in Gb
- Model 3 includes, in addition to model 2, a variable about the long life of battery in mAh that allows a longer temporal utilization of smartphones for fulfil needs of adopters.

Hierarchical regression calculates $\Delta R^2$ and $\Delta F$ to determine if model 2 and model 3 are better than model 1. The equations of regression analyses here are estimated using the Ordinary Least Squares method. Statistical analyses are performed with the Software IBM SPSS Statistics version 21.

## Results

Table 2 shows descriptive statistics, using a natural logarithmic scale. In general, variables in natural logarithm have normal distribution, except technical characteristics of Display in inches, 1st Camera Mpx, Processor and Memory. For these variables, if values not transformed in natural logarithmic scale have normal distribution, they are used in statistical analyses, otherwise variables not having normal distribution are not considered in statistical analyses. The normality of distribution of FMT is important to apply correct parametric analyses and reduce distortions and misleading results. Table 3 shows bivariate correlation between variables having normal distribution.

**Table 2.** *Descriptive statistics of technical characteristics of smartphone*

| | | *log* Price in Euros | *log* Display in inches | *log* Resolutio display pixels | *log* $1^{st}$ Camera megapixel | *log* $2^{nd}$ Camera megapixe | *log* Processor GHz | *log* Memory Gb | *log* RAM Gb | *log* Battery mAh |
|---|---|---|---|---|---|---|---|---|---|---|
| N | Valid | 735 | 733 | 733 | 724 | 624 | 673 | 716 | 656 | 727 |
| | Missing | 0 | 2 | 2 | 11 | 111 | 62 | 19 | 79 | 8 |
| Mean | | 5.206 | 1.551 | 13.735 | 2.303 | 1.416 | 0.414 | 2.710 | 0.717 | 7.792 |
| Std. Deviatioı | | 0.647 | 0.260 | 1.157 | 0.786 | 1.073 | 0.438 | 1.443 | 0.742 | 0.381 |
| Skewness | | -.034 | -2.018 | -1.094 | -1.528 | -1.111 | -2.597 | -1.669 | -.750 | -.783 |
| Std. Error of Skewness | | .090 | .090 | .090 | .091 | .098 | .094 | .091 | .095 | .091 |
| Kurtosis | | .379 | 4.125 | 1.174 | 4.507 | .780 | 12.780 | 4.083 | 2.346 | .092 |
| Std. Error of Kurtosis | | .180 | .180 | .180 | .181 | .195 | .188 | .182 | .191 | .181 |
| Minimum | | 3.07 | .372 | 9.704 | -1.204 | -1.204 | -2.283 | -5.298 | -3.219 | 6.620 |
| Maximum | | 7.44 | 1.917 | 15.931 | 4.220 | 3.332 | 1.030 | 5.545 | 3.466 | 8.517 |

Table 3 shows that the highest bivariate correlation is given by: *log* price and *log* resolution display in px ($r$=0.66, $p$-value=0.01), *log* price and processor GHz ($r$=0.61, $p$-value=0.01), *log* price and *log* RAM Gb ($r$=0.58, $p$-value=0.01), *log* price and display in inches ($r$=0.56, $p$-value=0.01). Coefficient of correlation is lower between *log* price and *log* battery MAh ($r$=0.51, $p$-value=0.01), *log* price and *log* $2^{nd}$ Camera Mpx ($r$=0.41, $p$-value=0.01).

**Table 3.** *Correlations*

| | | *log* Price Euro | *log* Resolution display pixels | *log* $2^{nd}$ Camera megapixel | *log* RAM Gb | *log* Battery mAh | Display in inches | Processor in Ghz |
|---|---|---|---|---|---|---|---|---|
| *log* Price Euro | Pearson Correlation | 1 | | | | | | |
| | Sig. (2-tailed) | | | | | | | |
| | N | 735 | | | | | | |
| *log* Resolution Display pixels | Pearson Correlation | .655** | 1 | | | | | |
| | Sig. (2-tailed) | .001 | | | | | | |
| | N | 733 | 733 | | | | | |
| *log* $2^{nd}$ Camera megapixels | Pearson Correlation | .408** | .673** | 1 | | | | |
| | Sig. (2-tailed) | .001 | .001 | | | | | |
| | N | 624 | 624 | 624 | | | | |
| *log* RAM Gb | Pearson Correlation | .575** | .714** | .736** | 1 | | | |
| | Sig. (2-tailed) | .001 | .001 | .001 | | | | |
| | N | 656 | 656 | 617 | 656 | | | |
| *log* Battery MAh | Pearson Correlation | .509** | .849** | .689** | .683** | 1 | | |
| | Sig. (2-tailed) | .001 | .001 | .001 | .001 | | | |
| | N | 727 | 727 | 624 | 654 | 727 | | |
| Display in inches | Pearson Correlation | .564** | .905** | .697** | .643** | .914** | 1 | |
| | Sig. (2-tailed) | .001 | .001 | .001 | .001 | .001 | | |
| | N | 733 | 733 | 624 | 656 | 727 | 733 | |
| Processor GHz | Pearson Correlation | .609** | .838** | .562** | .781** | .669** | .711** | 1 |
| | Sig. (2-tailed) | .001 | .001 | .001 | .001 | .001 | .001 | |
| | N | 673 | 673 | 609 | 638 | 670 | 673 | 673 |

**Note:** ** Correlation is significant at the 0.01 level (2-tailed).

Table 4 shows the arithmetic, geometric and exponential rates of growth of the technical characteristics of smartphone technology. Although differences of magnitude between these types of growth, the ranking of important technical characteristics having higher evolution is similar from the highest to lowest value between these different models. Table 4 shows, in decreasing order, that the technical characteristics in smartphone technology that have had the highest exponential growth $r_{exp}$ from 2008 to 2018 are respectively: Gb of memory=1.02; Gb of RAM=0.67, resolution display in px=0.62; Mpx of main camera= 0.54, Mpx of second camera=0.45. The lowest rates are for mAh of battery=0.19 and inches of display=0.16.

The first technical characteristic that, according to these rates in table 4, has had higher growth is memory Gb and RAM because of increasing needof smartphone to have large memory and RAM for allowing continuous updates of software applications and greater functionality (in fact, apps are more and more symbiotic technologies within complex systems of smartphones; Coccia, 2018h). The accelerated improvement of other technical characteristics (i.e., higher resolution of display and Mpx of cameras) is associated with visual perception of adopters that increase their satisfaction with better displays, images and videos (cf., Bhalla & Proffitt, 1999; Iriki *et al.,* 1996; Leutgeb *et al.,* 2005).

**Table 4.** *Rates of exponential, geometric and arithmetic growth in technical characteristics of smartphone technology from 2008 to 2018*

| Rates of growth | Memory Gb | RAM Gb | Resolution Display Pixels | 1st Camera Megapixels | 2nd Camera Megapixels | Processor GHz | Battery mAh | Display in inches |
|---|---|---|---|---|---|---|---|---|
| *r* exponentia | 1.015 | 0.668 | 0.623 | 0.542 | 0.454 | 0.331 | 0.190 | 0.155 |
| *r* geometric | 1.759 | 0.951 | 0.864 | 0.720 | 0.574 | 0.393 | 0.209 | 0.167 |
| *r* arithmetic | 2559.900 | 79.900 | 50.525 | 22.567 | 9.233 | 2.645 | 0.567 | 0.369 |

Table 5 suggests some symbols to indicate the intensity of growth of technological trajectories, measured with exponential rates of growth as illustrated in table 4. Hence, for instance, the evolutionary pathways of display in inches is \ = steady-state growth, main camera=+ (growth), and memory in Gb= ! (high development).

**Table 5.** *Scale for rating the acceleration of technological trajectories within complex systems of technology*

| Symbol | Description | Measure of the growth of technical characteristics with $r_{exp}$ |
|---|---|---|
| ! | High development of technological trajectory | $r_{exp}>1$ |
| + | Growth of technological trajectory | $0.5 \leq r_{exp} \leq 1$ |
| / | Steady-state technological trajectory | $r_{exp} < 0.5$ |

**Table 6.** *Estimated relationship for the evolution of smartphone technology (log-log model)*

*Dependent variable*: *log* Price

| Smartphone | *Unstandardized Coefficient* | *Standardized Coefficient* | *t-test* |
|---|---|---|---|
| Constant. α<br>(St. Err.) | 1.41<br>(0.80) | | 1.77 |
| Coefficient *log* Resolution Display in pixels<br>(St. Err.) | 0.44***<br>(0.04) | 0.58 | 11.62 |
| Coefficient *log* 2nd Camera megapixel<br>(St. Err.) | −0.05*<br>(0.03) | −0.1 | −2.06 |
| Coefficient *log* RAM Gb<br>(St. Err.) | 0.27***<br>(0.05) | 0.30 | 2.50 |
| Coefficient *log* Battery mAh<br>(St. Err.) | −0.32***<br>(0.1) | −0.15 | −3.23 |
| *$R^2$ adj. adj.*<br>*(St. Err. of the Estimate)* | 0.44<br>(0.43) | | |
| *F*<br>*(sign.)* | 124.16<br>(0.001) | | |

**Note:** *** *p-value*< .001 ** *p-value*< .010 * *p-value*< .050

Table 6 shows that the evolutionary pathways of smartphone technology is, in average, driven by resolution of display in pixels and performance of RAM in Gb as suggested by standardized coefficients of regression. Moreover, the OLS estimation of model in table 6 indicates that a 1% higher level of quality in Display resolution increases the expected price of smartphone by about 0.44% (*p*-value<.001), whereas a 1% higher level of Gb in RAM increases the expected price of smartphone by about 0.27% (*p*-value<.001). Using the multiple regression analysis with stepwise method (Criteria: Probability-of-*F*-to-enter <= .050, Probability-of-*F*-to-remove >= .100), $R^2$ adjusted of the model indicates that about 42% of the variation in price can be attributed (linearly) to the resolution of display in px as predictor. Table 7 shows that models with other variables entered increase the goodness of fit of about 2%, achieving 44% with four predictors (cf., model 4d. in Tab. 7).

**Table 7.** *Model summary with stepwise method*

| *Model* | *Adjusted R Square (std. error of the estimate)* | *F* | *Sign.* |
|---|---|---|---|
| 1 a. | 0.415 (0.438) | 436.27 | 0.001 |
| 2 b. | 0.427 (0.433) | 230.86 | 0.001 |
| 3 c. | 0.441 (0.428) | 163.27 | 0.001 |
| 4 d. | 0.444 (0.427) | 124.16 | 0.001 |

**Note:** Dependent variable is *log* price in euros.

a. Predictors: (Constant), *log* resolution display in px
b. Predictors: (Constant), *log* resolution display in px, *log* RAM in Gb
c. Predictors: (Constant), *log* resolution display in px, *log* RAM in Gb, *log* Battery in mAh
d. Predictors: (Constant), *log* resolution display in px, *log* RAM in Gb, *log* Battery in mAh, *log* second camera in Mpx

**Table 8.** *Hierarchical regression analysis of predictors of smartphone prices*

| | *Model 1* | *Model 2* | *Model 3* |
|---|---|---|---|
| *Constant* $\lambda_0$ | −1.94*** | −0.61 | 1.41 |
| *(St. Err.)* | (0.43) | (0.50) | (0.80) |
| *log* (Resolution Display in Pixels) | | | |
| *Coefficient* $\lambda_1$ | 0.52*** | 0.41*** | 0.44*** |
| *(St. Err.)* | (0.03) | (0.04) | (0.04) |
| *log* 2nd camera in Megapixels | | | |
| *Coefficient* $\lambda_2$ | −0.02 | −0.08*** | −0.05* |
| *(St. Err.)* | (0.02) | (0.03) | (0.03) |
| *log* RAM Gb | | | |
| *Coefficient* $\lambda_3$ | | 0.24*** | 0.27*** |
| *(St. Err.)* | | (0.05) | (0.05) |
| *log* Battery mAh | | | |
| *Coefficient* $\lambda_4$ | | | −0.32*** |
| *(St. Err.)* | | | (0.10 |
| *F* | 218.56 | 159.61 | 124.16 |
| *Sig.* | 0.001 | 0.001 | 0.001 |
| $R^2$ *adj.* | 0.41 | 0.436 | 0.444 |
| *(St. Err. of the Estimate)* | (0.44) | (0.43) | (0.43) |
| $\Delta R^2$ | 0.41 | 0.023 | 0.009 |
| $\Delta F$ | 218.56*** | 24.78*** | 10.43*** |

**Note:** Dependent variable: *Log* Price. *** = *p-value* < .001 ** = *p-value* < .010 * = *p-value* < .050

Models of hierarchical regression in table 8 show that Model 1 of the hierarchical ordering including technical characteristics of smartphone that interact with visual perception of adopters (resolution display in pixels and second camera in Mpx), entered together, contribute significantly: $R^2$ adjusted of the model indicates that about 41% of the variation in price can be attributed (linearly) to these technical characteristics. Other variables, such as main camera, are not included because they have not normal distribution. At next stage, in model 2, the technical characteristic of storage and functionality of smartphones given by RAM in Gb explains about 2.3% of the variance accuracy scores over and above the technical characteristics associated with visual perception of adopters, which is a significant amount (*p*-value<0.001). At the next stage, in model 3, the long life of battery in mAh explains about 1% of the variance accuracy scores over and above the technical characteristics associated with visual perception of adopters and the technical characteristic of storage and functionality of smartphones given by RAM in Gb (*p*-value<0.001).

Table 9 shows descriptive statistics of the evolutionary improvements of technical characteristics in smartphone technology from 2008 to 2018. The maximum value indicates the highest level achieved by technical characteristics in 2018.

**Table 9.** *Descriptive statistics of the evolutionary stepwise improvements of technical characteristics in smartphone technology from 2008 to 2018*

| Technical characteristics | N | Minimum | Maximum | Mean | Std. Deviation |
|---|---|---|---|---|---|
| Display in inches | 55 | 1.45 | 6.80 | 4.44 | 1.49 |
| Resolution Display total pixels | 33 | 16384.00 | 8294400.00 | 1411271.03 | 1845077.45 |
| $1^{st}$ Camera megapixels | 38 | 0.30 | 68.00 | 18.50 | 13.72 |
| $2^{nd}$ Camera megapixels | 25 | 0.30 | 28.00 | 7.85 | 8.25 |
| Processor GHz | 29 | 0.10 | 2.80 | 1.45 | 0.81 |
| Memory Gb | 30 | 0.01 | 256.00 | 17.25 | 52.02 |
| RAM Gb | 15 | 0.04 | 32.00 | 4.96 | 8.39 |
| Battery MAh | 123 | 750.00 | 5000.00 | 2411.87 | 931.22 |

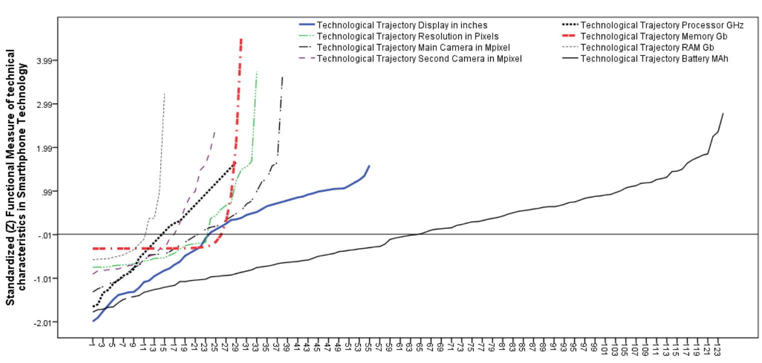


**Figure 1.** *Technological trajectories of the evolution of smartphone technology from 2008 to 2018*

Figure 1 shows the representation of technological trajectories of the evolutionary improvements of technical characteristics in smartphone technology from 2008 to 2018. Figure 1 reveals two patterns of technological evolution of these characteristics in smartphone technology:

- *Arithmetic* growth of technological trajectories is for the technological characteristics of battery in mAh, display in inches, and processor in GHz.
- *Exponential* growth of technological trajectories is for the technological characteristics of RAM in Gb, 1st and 2nd camera in Mpx, memory in Gb and resolution in total pixels.

Therefore, representation of the evolution of technological trajectories from 2008 to 2018 in Figure 1 suggests that smartphone technology is driven mainly by technological characteristics associate with visual perception of adopters (high definition of display and camera), storage (memory) and functionality with RAM in Gb.

**Table 10.** *Estimated relationships of evolutionary improvements of technical characteristics in smartphone technology*

| Models | *Mod. 1 linear* | *Mod. 2 linear* | *Mod. 3 linear* | *Mod. 4 Exp* | *Mod. 5 Exp* | *Mod. 6 Exp* | *Mod. 7 linear* | *Mod.8 linear* |
|---|---|---|---|---|---|---|---|---|
| *Constant* $\beta_0$ | 1.88*** | 792.52*** | 0.02 | 2.35*** | 0.48*** | 10.27*** | –4.33*** | –3.04*** |
| *(St. Err.)* | (0.08) | (26.95) | (0.01) | (0.37) | (0.04) | (0.14) | (0.36) | (0.14) |
| Display in inches *Coefficient* $\beta_1$ | 0.09*** | | | | | | | |
| *(St. Err.)* | (0.002) | | | | | | | |
| Battery mAh *Coefficient* $\beta_2$ | | 25.73*** | | | | | | |
| *(St. Err.)* | | (0.37) | | | | | | |
| Processor Ghz *Coefficient* $\beta_3$ | | | 0.10*** | | | | | |
| *(St. Err.)* | | | (0.001) | | | | | |
| 1st Camera Mpx *Coefficient* $\beta_4$ | | | | 0.09*** | | | | |
| *(St. Err.)* | | | | (0.007) | | | | |
| 2nd Camera Mpx *Coefficient* $\beta_5$ | | | | | 0.17*** | | | |
| *(St. Err.)* | | | | | (0.005) | | | |
| *log*Resolution px *Coefficient* $\beta_6$ | | | | | | 0.014*** | | |
| *(St. Err.)* | | | | | | (0.001) | | |
| *log*Memory Gb *Coefficient* $\beta_7$ | | | | | | | 0.26*** | |
| *(St. Err.)* | | | | | | | (0.02) | |
| *log*RAM Gb *Coefficient* $\beta_8$ | | | | | | | | 0.42*** |
| *(St. Err.)* | | | | | | | | (0.02) |
| *F* | 1420.28 | 4766.17 | 14001.71 | 149.99 | 1176.20 | 391.32 | 159.38 | 772.84 |
| *Sig.* | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| $R^2$ *adj.* | 0.96 | 0.98 | 0.998 | 0.80 | 0.98 | 0.92 | 0.85 | 0.98 |
| *(St. Err. of the Estimate)* | (0.29) | (147.13) | (0.04) | (0.48) | (0.18) | (0.04) | (0.97) | (0.25) |

**Note:** Dependent variable: temporal steps from 2008 to 2018; px is acronyms of pixel. *** = *p-value* < .001 ** = *p-value* < .010 * = *p-value* < .050

Table 10 shows the parametric estimates of linear or exponential models of the technological evolution of technical characteristics in smartphone technology. Results are consistent with previous statistical analyses. The $R^2$ values are nevertheless very high. Thus in majority of cases models explain more than 90% variance in the data.

## Discussionand concluding observations

This article proposes a hedonic price method for the analysis of the most important technical characteristics supporting the evolution of smartphone technology. In particular, the approach here is based on a simple assumption that technologies are complex systems based on interrelated sub-systems of technologies. The approach is formalized with a simple *log-log model of hedonic pricing*, which is useful to be generalized in order to predict which technical characteristics within complex systems of technology (e.g., smartphone) are likeliest to evolve rapidly. This approach seems also to be appropriate to detect evolutionary pathways of new technology that may sustain competitive advantage of firms and fulfil needs of adopters in markets.

The results here are that evolutionary pathways of smartphone technology are, in average, driven by display resolution in pixel and performance of RAM in Gb as suggested by standardized coefficients of regression.

In particular, hierarchical regression suggests that technical characteristics of smartphone that interact with visual perception of adopters (resolution display in pixels and second camera in Mpx) contribute significantly to technological evolution of this ICT. This result is represented in figure 1 that shows *exponentialgrowth* of the technological characteristics of RAM in Gb, 1$^{st}$ and 2$^{nd}$ camera in Mpx, memory in Gb and resolution in total pixels, whereas other technical characteristics have arithmetic pathways of growth.

This result of smartphone technology is consistent with the market of digital cameras that shows how the evolutionary pathway of resolution from 1998 to 2001 is increased from around 0.5 to more than 1.5 megapixels (Carranza, 2010). This finding indicates that the long-run evolution of smartphone technology depends on the behavior and evolution of associated technologies (cf., Sahal, 1981, Coccia, 2017b). In fact, the evolution of smartphone technology, as a complex system, is driven by a coevolution of innovations in digital cameras and other technologies, such as resolution HD, full HD, Quad HD or 2K, 4K or Ultra HD as well as new technology for displays, e.g., LCD, OLED, AMOLED, Super AMOLED, TFT-LCD, Retina, etc. As a matter of fact, evolutionary pathways of smartphone technology are due to the effects of cumulative learning from digital technology (cf., Watanabe *et al.,* 2012). In particular, learning effects, based on learning by doing and learning by using, are fostering the assimilation of new technology in smartphone devices (Cohen & Levinthal, 1990). Sahal (1981, p.82, original italics) argues that: "the role of learning in the *evolution* of a technique has profound implications for its *diffusion* as well". Williams *et al.,* (2000) suggest: "a concept of domestication which tames assimilated spillover technology for a whole institutional system in a co-evolutionary way" (as quoted by Watanabe *et al.,* 2012, p.1293). Watanabe *et al.,* (2012, pp.1293-1294) claim that mobile phones can attract a vast spectrum of adopters by incorporating "super-functionality, and…. users are transformed into explorers in search of further exciting stories based on their own initiative and this then thrills them with gratification of such exploration".In general, this study shows that the evolution of technology is driven by the interaction between smartphone technology and its subsystem components, e.g., displays, camera, etc. that drive the evolutionary pathways of these complex systems of technology and technological diversification over time and space (cf., Coccia, 2017b). The finding of this study could aid technology policy and management of technology to design best practices for supporting the development of technological trajectories with faster rates of growth. The hedonic price method applied here for assessing technological evolution is useful for: "products that can be represented as sets of characteristics and for which both characteristics values and corresponding prices are known for a sufficiently large number of models" (Saviotti, 1985, p.314-315). In addition, within competitive markets, well informed adopters are available to pay a given price for a product only if the levels of characteristics supplied satisfy their requirements. The analysis of the evolution of technological characteristics and pricing behavior of different products within smartphone industry can therefore serve to compare the performance of different technologies and provide information of its technical progress and evolutionary pathways.

However, drawbacks of the approach here to analysis of the evolution of technology are that hedonic pricing function cannot, in general, be rigorously derived from theories of consumer demand or from the production function. Its theoretical status is still not clear (cf., Saviotti, 1985, Triplett, 1985). In short, hedonic pricing applied to technological evolution needs improvements in the theoretical framework and its empirical evidence. Some of the methodological issues (e.g., choice of variables, data collection, etc.) are common to all methods of technology analysis, while others are specific to the hedonic price method. For instance, a price-technological characteristics relationship should only be applicable to a homogeneous market (Muellbauer, 1974, p.988). Saviotti (1985, p.334, original emphasis) also argues that: “the hedonic price method cannot be used in an ‘unskilled’ way to measure changes in technology”. Of course, this approach requires an accurate knowledge of the technology under study.

To conclude, the proposed approach here keeps its validity in explaining specific technological characteristics supporting the evolutionary pathways of a given technology, such as smartphone. In particular, this study constitutes an initial significant step in the application of hedonic pricing method to study the evolution of technology considering the interaction between technologies in complex systems to predict fruitful technological trajectories. Hence, this study may lay the foundation for development of more sophisticated theoretical frameworks in technology analysis and technological forecasting, using hedonic pricing, to detect and forecast the evolutionary technological trajectories of a given complex system of technology. Nevertheless, the identification of a comprehensive method for detecting critical pathways of the evolution of technology that depends on the behavior of the other technologies is a non-trivial exercise, because manifold factors are not equal over time and space as well as between different technologies. Wright (1997, p.1562) properly claims that: “In the world of technological change, bounded rationality is the rule.”

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# 13. Conclusion

Fundamental questions in the research fields of science and technology are: How the concept of science and innovation has been studied in the course of time? What taxonomy of technological innovation is the most desirable to explain evolutionary pathways? How technologies evolve over time and space? And what are the manifold sources of science and technology in society? Finally, how technological innovation can be measured to predict which technologies are likeliest to evolve rapidly?

These questions are some of scientific issues that have been inadequately addressed in social studies of science and technology, yet they offer exciting entry points into the current discussion of these research fields. This book here endeavors to clarify these questions to explain and generalize, as far as possible, some temporal and spatial aspects of the origin and evolution of science and technology in society supporting economic growth of nation. Moreover, given the exponential growth in the literature of science and technology, the next decade should witness substantial progress in our understanding of converging pathways in science and patterns of technological innovation in all its various guises. On a broader plain, social studies of science and innovation have made great strides in developing a body of theory that complements biological evolutionary theory. There is every reason to suspect that this trend will continue, and the chapters in this volume strongly support that claim.

Overall, then, this book can lay a foundation for the development of more sophisticated concepts and theories to explain technological, scientific and economic change in human society. Future research will expand this *terra incognita* to refine technology and science analysis, also showing positive and negative sides in society.

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