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How does science advance? Theories of the evolution of science

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Abstract. This study presents different theories of the evolution of science to explain how science and its scientific fields evolve over the course of time. In particular, this study clarifies, as far as possible, models and properties of the scientific development to understand structure, dynamics and drivers of the scientific and technological evolution in society.

Keywords. Scientific development, Evolution of science, Scientific research, Structure of science, Research fields, Economics of science, Political economy of science, Technological change, Research labs.
JEL. A19, C00, I23, L30.

1. Introduction

The main goal of this paper is to explain the models and laws of scientific development to clarify whenever possible dynamics, general properties and characteristics of the evolution of science over time and space.

The philosophy, history, sociology, scientometrics and economics of science have produced valuable insights into the nature and dynamics of science as a human activity and social system (Börner *et al.,*, 2011, 2012). This research field of "The science of science" can offer a deeper understanding of the driving factors of successful science to address economic, social and technological problems (Fortunato *et al.,*, 2018). In this context, the study here is part of a large body of research on the evolution of science that explains how science evolves in human society to clarify and forecast the structure and evolution of research fields in applied and basic sciences (Coccia, 2018; 2020a; Coccia & Bozeman, 2016; Coccia & Wang, 2016; Scharnhorst *et al.*, 2012; Sun *et al.,*, 2013)[1]. In particular, this paper describes major theories and laws to clarify the science dynamics. Results of this study may afford an interesting opening into the exploration of properties that explain and generalize, whenever possible, the evolution of science and its scientific disciplines.

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[1] Many social studies of science investigate these topics with different perspectives, such as Adams, 2012; Ávila-Robinson *et al.,*, 2019; Freedman, 1960; Kuhn, 1962; Lakatos, 1968, 1978; Merton, 1957, 1968; Stephan, 1996; Stephan and Levin, 1992.

The paper starts with a section about key concepts of evolution, science and scientific research that define terminology used in this study here. This section is followed by main theories of scientific development in the history, philosophy, and sociology of science. The subsequent section shows specific laws and models for the analysis of the evolution of science in which scientific development is inter-related to the diffusion of ideas. The paper concludes with general model of the evolution of science and possible relevance of this study for science and research policy.

2. Theoretical background

A brief background of vital concepts is useful to clarify the study here. First of all, the concept *evolution* refers to a progressive growth of systems. The word 'evolution' was first applied to natural phenomena by the German biologist Albrecht von Haller in 1744 (cf., Richards, 1992). Spencer (1857) popularizes the term 'evolution' that can be associated with different types of phenomena, including all feasible manifestations of development and change (cf., Coccia, 2019a; Coccia & Watts, 2020). The evolution can be due to self-organization or spontaneous order of complex systems (Coccia, 2019a). The vital concept under study here is *science*: "ordered knowledge of natural phenomena and the rational study of the relations between the concepts in which those phenomena are expressed" (Dampier, 1953). Kuhn (1962) claims 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". Rae (1834, p.254) states that the aim of science may be to ascertain the manner in which things actually exist. Russell (1952) provides a broader definition of: "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". Instead, Russell (1952) describes science as static, whereas it is a dynamic process. According to Freedman (1960), the definition by Russell (1952) is 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. As result, Freedman (1960, p.3) suggests a comprehensive definition, whenever possible, of science as follows: "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". In this context, Seidman (1987, pp.131-135) states that:

> science is an organized and collective activity (p. 131) …scientific development occurs in a dynamic relation to the encompassing social

> context (p. 134) …. Society is constitutive of science not merely in the sense of forming a normative context enhancing or impeding scientific rationality, but in that it informs the very processes of inquiry, e.g., problem-selection, the constitution of the scientific domain, the determination of facts, the very research results, and criteria of validity and truth. Science must be treated like any other symbolic form—namely as a mode of structuring reality embedded in the social structure of the whole society (p. 135)[2].

In general, science is a process in which scholars and institutions coordinate their actions by using appropriate strategies, methods of inquiry and instruments to generate new knowledge that is recorded in journals articles, books, patents, software repositories, etc. (Whitley, 1984; cf., Coccia & Benati, 2018). This process of science generates an accumulation of knowledge in basic and applied fields of research (Coccia, 2019; Godin, 2001). Börner *et al.,* (2012, p.3) claims that: "Science is in a constant state of flux. Indeed, one of the purposes of science is to continually generate new knowledge, to search for or create the next breakthrough that will open new doors of understanding". Fortunato *et al.,* (2018) describe science as: "a complex, self-organizing and evolving network of scholars, projects, papers and ides". Shi *et al.,* (2015) also consider science as a complex and dynamic network in which scientists, institutions, concepts, physical entities and other forces "knit, weave and knot" (Latour, 1987, p.94) together into an overarching scientific fabric (Latour, 1999; Latour & Woolgar, 1979; Callon, 1986). Shi *et al.,* (2015) model the outcome of this complex assembly process as a dynamic hypergraph[3] in which articles are hyperedges that contain nodes of distinct types providing a substrate for future scientific discoveries. This approach extends a classic network-oriented perspective on human problem solving and suggests that science is not just a network of dyadic ties but it is also a collection of garbage cans in which problems and solutions are mixed randomly (cf., Newell & Simon, 1972, p.51; the garbage-can model by March and Simon in Cohen *et al.,*, 1972). Science as a complex and dynamic network develops and changes over time (Fortunato *et al.,*, 2018). In this context, Van Raan & Peters (1989, p.607) discuss the possibility to represent scientific development by 'second-order networks' structured with subfield-to-subfield relations that can reveal dynamical processes in the evolution of research fields. Other studies have investigated the structure of science using maps that show scientific landscape to identify major fields of science, their size, similarity and

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[2] See also Bernal, 1939; Bush, 1945; Callon, 1994; Etzkowitz and Leydesdorff, 1998; Johnson, 1972; Nelson, 1962; Nelson and Romer, 1996; Rosenberg, 1974.

[3] Hypergraphs are mathematically equivalent to bipartite graphs in which articles (hyperedges) are represented as a distinct type of node that connects other *things* together. Latour points out that the old word "Thing" originally designated a type of archaic assembly, as the Icelandic Althing: "Thus, long before designating an object thrown out of the political sphere and standing there objectively and independently, the Ding or Thing has for many centuries meant the issue that brings people together because it divides them" (as quoted by Shi *et al.,*, 2015, p. 73).

interconnectedness (Börner & Scharnhorst, 2009; Boyack *et al*.,, 2005, 2009; Klavans & Boyack, 2009; Simonton, 2004), the role of social interactions in shaping the dynamics of science and the emergence of new disciplines (Börner *et al*.,, 2011; Tijssen, 2010; Sun *et al*.,, 2013; Van Raan, 2000)[4], the convergence between research fields considering international research collaboration (Coccia & Bozeman, 2016; Coccia & Wang, 2016), etc. Another basic concept here is *scientific research*: it is a continued search for advancing scientific knowledge, applying methods of inquiry (Coccia, 2018a; Coccia & Benati, 2018). Kot (1987) argues that science is a dynamic system governed by flows of scientific information, which are fuelled by scientific research based on continued search for scientific knowledge and understanding by scientific methods of inquiry (cf., Foote, 2007; Evans & Foster, 2011). Lievrouw (1988, p.7*ff*) proposes that scientific researchers can be organized into four distinct "programs" of study:

1. Artifact studies: scientific information as an objective commodity, whose value is independent of its use;
2. User studies: scientific information as a commodity whose value depends on the practical needs of the user;
3. Network studies: scientific information as a social link, whose value is determined by its utility in the coherence of social networks;
4. Lab studies: scientific information as a social construction of scientists, with its value completely dependent on the changing perceptions of those individual scientists (so called because their authors typically employ participant observation or other ethnographic techniques to gather data in the scientists' workplace).

Moreover, social studies of science categorize science in basic and applied fields of research: basic research is aiming at finding truth, whereas applied research is aiming at solving practical problems (Kitcher, 2001; Frame & Carpenter, 1979; Fanelli & Glänzel, 2013). Frame & Carpenter (1979) suggest that basic fields include mathematics, astronomy (similar to space science), physics and chemistry; and applied research fields include biology, clinical medicine, and engineering/technology. Storer (1967) focuses on the concept of hard and soft to characterize different branches of science. In particular, Storer (1967, p.75, original emphasis) claims that: “The degree of rigor seems directly related to the extent to which mathematics is used in a science, and it is this that makes a science ‘hard’ ”. Storer (1967) suggests that chemistry and physics have the same “rated hardness”, i.e., they are characterized by a high degree of rigor. Overall, then, social studies of science aim to explain specific questions, such as the structure and dynamics of science (Coccia, 2018; Coccia & Wang, 2016; cf., Sintonen, 1990; Sun *et al*.,, 2013). This study here is interested to review major theories and models of scientific development that can provide an interesting opening into the exploration of properties that clarify and

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[4] cf., Boyack, 2004; Boyack *et al*.,, 2005; Fanelli & Glänzel, 2013; Simonton, 2002; Small, 1999; Smith *et al*.,, 2000; Sun *et al*.,, 2013.

predict, whenever possible, the development of science for progress in society.

3. Theories of the evolution of science

Science is a complex system with dynamic elements (e.g., disciplines and research fields) that develop over time (Coccia, 2020a, 2019c). The evolution of science is critical to explain human progress (Coccia & Bellitto, 2018). The most prevalent theories of scientific development are:

- theory of the accumulation of knowledge
- theory of scientific paradigm shifts by Khun
- theory of research programme by Lakatos
- theory by Tiryakian
- theoretical revisionism by Alexander Jeffrey
- theory of openness, closure and branching described by Mulkay

The main characteristics of these theories are briefly described as follows.

☐ *The cumulative theoryof knowledge*

Science is an activity of accumulation (Science, 1965). The cumulative theory states that scientific development is due to a gradual growth of knowledge based on a sum of facts accumulated by scholars, institutions and other actors (Haskins, 1965; Godin, 2001). In particular, Seidman (1987, pp.121-122) argues that: "The cumulative addition of facts and verified propositions, conceptual refinements, or analytical developments dislodge erroneous theories, and propels us toward theories which are closer to the truth about society…. virtually every current social scientific theory strives to achieve legitimacy and dominance by reconstructing the past as a cumulative development crystallizing in its own systematization". In this context of the accumulation of knowledge, basic and applied sciences evolve and converge creating a deeper unity within the overall structure of science (Coccia & Wang, 2016; Haskins, 1965). Moreover, in this approach the evolution of science is irreversible and can never go back (Science, 1965).

☐ *The model of scientific paradigm shifts by Khun*

The scientific development is due to accumulation of "normal science"[5], interrupted by discontinuous transformations generated by new theoretical and empirical approaches that support the transition from an existing scientific paradigm to an emerging one. In fact, paradigm shifts are the major source of scientific change in society (Kuhn, 1962). Scientific paradigm shifts can have a significant impact on several disciplines (e.g., the pervasive effect of artificial intelligence in different research fields and technologies; cf., Coccia, 2020) or can have consequences within a specific scientific discipline in which the change has taken place (e.g., the impact of

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[5] " 'normal science' means research firmly based upon one or more past scientific achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice'' (Kuhn, 1962, p.10, original emphasis).

the discovery of quasicrystals into the field of condensed matter; cf., Andersen, 1998, p. 3; Coccia, 2016). Moreover, in this theory, scientific paradigm shift can be *major* in the presence of discontinuity with previous theoretical framework (e.g., target therapy vs. chemotherapy in cancer treatments; cf. Coccia, 2012b, 2012c, 2014a, 2015a, 2016a), and *minor* whether it generates continuity between successive paradigms (e.g., nanoparticle-delivered chemotherapy in oncology that combines traditional chemotherapy and emerging nanotechnologies; Coccia & Wang, 2015; cf., Clark, 1987; Coccia & Finardi, 2012). Hence, Kuhn (1962) focuses on revolutions in science that generate a scientific paradigm shift that has been accepted by a community of scientists, and is used as a basis for their scientific work. In general, major or minor paradigm shifts support the long-run evolution of science, disciplines and research fields over time.

☐ *The theory of scientific programme by Lakatos*

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 - …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).

Lakatos' theory of research programme is based on a hard core of theoretical assumptions that cannot be abandoned or altered without abandoning the programme altogether. The evolution of science here is due to the creation of a research programme that guides the scientific development of one or more research fields and/or disciplines over time (Lakatos, 1978). For instance, the Human Genome Project (HGP) is a collaborative research program whose goal was the complete mapping and understanding of all the genes of human beings (all genes together are known as our genome). HGP is a resource of detailed information about the structure, organization and function of the complete set of human genes for explaining the development and function of a human being in different research fields of science (NHGRI, 2020). Finally, Lakatos' theory also argues that a research programme, in the presence of troublesome anomalies, remains progressive despite them.

☐ *The theory by Tiryakian for scientific development*

Tiryakian (1979) argues that the *scientific school* is the unit of analysis for a model of scientific development. Major schools develop scientific disciplines by providing new methodologies or new conceptual schemes of social reality. Tiryakian (1979) rejects both the empiricist approach that discoveries initiate scientific change and the rationalist claim that conceptual refinements of theoretical models stimulate a scientific change. In short, the formation of a school offers new scientific directions to study social reality that initiates significant scientific advances over time (e.g., in economics, the Monetarism is a school of thought based on control of money to affect price levels and economic growth *versus* Keynesian economics based on government expenditures with fiscal policy to support economic development).

☐ *The revisionism by Alexander Jeffrey for scientific development*

Seidman (1987) argues that: "the discovery of anomalies or analytical criticisms of one or another dimension of a theory sets in motion a process of theoretical revision". Unlike Kuhn (1962), Alexander (1979) proposes that scientific theories do not change in a revolutionary manner. Scientific theories are based on different autonomous entities, such as presuppositions, ideologies, models, laws, concepts, propositions, methodologies, etc. that shape science, articulate its problems, and have a distinctive mode of discourse with its own standards of assessment. In short, Tiryakian (1979) analyses the tensions and dynamics of the social structure of the school and its relation to scientific community. By contrast, Alexander (1983, p.349) argues that the engine of scientific change is due to new theoretical frameworks of scholars that generate a revision of current conceptual scheme in specific fields of research, marking the life-history of a school and discipline.

☐ *Models of scientific progress: openness, closure and networking*

The theories of openness in science

The theories of openness argue that science and technology are most likely to flourish in democratic society because science and technology have democratic values and democratic nations do not have barriers towards discoveries and new technology (cf., Coccia, 2005b, 2010, 2017d, 2019d). In this context, scientific breakthroughs can be advances of knowledge if findings are made accessible to the critical inspection of other scholars in scientific community. In short, researchers have to communicate new results and data to other scholars, facilitating the reproducibility of results for validation of findings and/or new theories. Researchers, producing and sharing discoveries, are rewarded with a higher reputation and recognition in scientific communities, increasing the diffusion of their theories, the citations of their research articles and the funds for research, etc. (cf., Coccia, 2019; Merton, 1968; Bol *et al*.,, 2018). Hence, science, within open research communities and democratic settings, will grow rapidly because there is low resistance to new scientific ideas and technologies (De Solla Price, 1986; Kitcher, 2001; Merton, 1957; Mulkay, 1969; Coccia, 2010).

The theory of closure in science

Polanyi (1958) argues that scientists are often not open-minded, independent puzzle-solvers, but rather men devoted to solving a limited range of problems rigidly defined by their scientific group. The history of science shows the existence of scientific orthodoxies, which tend to generate intellectual resistance in scientific progress (Cohen, 1952). This approach is consistent with the nature of scientific education that produces intellectual conformity from old generation of scholars to new ones. Mulkay (1975, p.514) argues that the advances of scientific knowledge in Kuhn's theory are due to intellectual closure, rather than intellectual openness of scholars. In particular, the scientific evolution is due to an open rebellion against the existing paradigm created by intellectual orthodoxy (Cohen, 1952). In fact, scientific paradigm shift is mainly due to an accumulation of anomalies that cannot be answered within existing scientific rules or theories. These anomalies of existing paradigms lead to few scholars to think in wholly new directions, changing accepted paradigms in science and giving a new conceptual scheme (Boring, 1927). For instance, Büttner *et al.*, (2003, pp.38-39) state that in the 1900s, the establishment of the radiation spectrum by precision measurements and its description by Planck’s formula creates an anomaly and a crisis in classical physics. Max Planck attempts to derive his radiation formula on the basis of classical physics, involving in an error. Albert Einstein discovers the error in Planck’s classical derivation and suggests a quantum derivation of radiation law. This new approach discards existing scientific paradigm and establishes aspects of a new paradigm that, however, was not immediately recognized as the solution of the problem. The authoritative lecture in 1908 by the recognized master of classical physics, H.A. Lorentz, validated the discovery and the widespread acceptance of this new paradigm in physics. Planck (1950, pp.33-34) states that: “a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it”. For instance, the discovery of quasicrystals in 1982 by Shechtman *et al.*, (1984) was a remarkable and controversial finding, violating the textbook principles of solid state materials. The interpretation that these materials are a new type of solid was disputed vigorously by Pauling (1987), American Chemist with two Nobel Prizes. At the end of his life, Pauling (1987) remained the only prominent opponent to quasiperiodicity in crystals. As a matter of fact, the evolution of science is due to: “a series of battles in which innovators have been forced to fight against the entrenched ideas of fellow scientists” (Mulkay, 1975, p.12).

The theories of networking and branching in science

Science can evolve with social and research networks of scholars (Adams, 2012, 2013). Adams (2012, p.335) claims that: “New collaboration patterns are changing the global balance of science" (cf., Coccia, 2019f). The evolution of any one research network depends on developments in neighbouring scientific fields in the geography of science. In this context, Mulkay (1975) argues that the exploration of new research fields generates a scientific migration of scholars from established research networks that are declining in terms of significant results to emerging research fields (Bettencourt *et al.,*, 2009; Coccia, 2018; Crane, 1972; Guimera *et al.,*, 2005; Mullins, 1973; Wagner, 2008). In this approach, leading scholars create research teams investigating new topics that have international scientific collaborations in new research networks (cf., Coccia, 2018, 2018d, 2019e). For instance, Relman (2002), American microbiologist, produces one of the first articles that investigates the human microbiome, creating a research team at Stanford University School of Medicine in California to develop the general themes of host-microbe interactions and human microbial ecology (Coccia, 2018). This new research field brings together scientific communities that collaborate in the environmental, animal and biomedical microbiome arenas for presenting new researches, methodologies and trends in microbiome research.In this context, Sun *et al.,* (2013, p. 4) claim that the socio-cognitive interactions of scientists and scientific communities play a vital role in shaping the evolution of science. Sun *et al.,* (2013) also argue that research fields evolve from diversification and/or merger of scientific communities within collaboration networks. This literature of social construction of science has investigated international collaborations between research organizations because foster scientific breakthroughs, technological advances, and other events that are fundamental determinants of the social dynamics of science[6]. Morillo *et al.,* (2003, p.1237) claim that research fields are increasing the interdisciplinary because of a combination of different bodies of knowledge and new communities of scholars from different disciplines that endeavour to solve more and more complex problems in nature and society[7]. Sun *et al.,* (2013) argue that theories of science dynamics have attributed the evolution of fields to branching, caused by new discoveries or processes of specialization and fragmentation in science (cf., Coccia, 2020a; Mulkay, 1975; Noyons and van Raan, 1998; Wray, 2005). For instance, physics and astronomy have produced multiple research fields that evolve autonomously in science, such as radio astronomy in 1932; in turn, from radio astronomy a branching process has generated new research fields of scientific specialization for studying quasars since1950-1963, pulsars since 1967, etc. (cf., Fig. 1; Mulkay, 1975, p.518*ff*; the concept of scientific fission by Coccia, 2020a). Small (1999, p.812) argues that: "the location of a field can occasionally defy

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[6] cf., Beaver and Rosen, 1978; Coccia and Bozeman, 2016; Coccia and Wang, 2016; Coccia and Rolfo, 2008, 2009; Coccia *et al.,*, 2015; De Solla Price, 1986; Frame and Carpenter, 1979; Latour, 1987; Latour and Woolgar, 1979; Mulkay, 1975; Newman, 2001; Sun *et al.,*, 2013; Storer, 1970.

[7] Coccia, 2012, 2012a; Fanelli and Glänzel, 2013; Gibbons *et al.,*, 1994; Guimera *et al.,*, 2005; Kitcher, 2001; Sun *et al.,*, 2013; Wagner, 2008.

its disciplinary origins". In fact, Sun *et al.*, (2013, original emphasis) claim that: "new scientific fields emerge from *splitting* and merging of …social communities. Splitting can account for branching mechanisms such as specialization and fragmentation, while merging can capture the synthesis of new fields from old ones. The birth and evolution of disciplines is thus guided mainly by the social interactions among scientists".

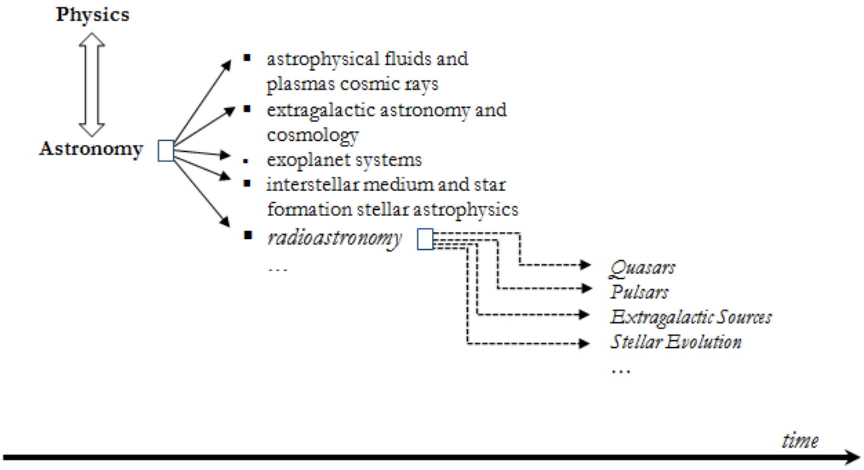

Figure 1. *Branching from physics-astronomy, radio astronomy to studies of quasars and other exotic objects in space*

The determinants of breaching and scientific specialization can be due to a process of convergence between basic and applied sciences, from a specialization within applied or basic sciences or through the combination of multiple disciplines (cf., Coccia & Wang, 2016; Coccia, 2020a; Jamali & Nicholas, 2010; Jeffrey, 2003; Riesch, 2014; van Raan, 2000; Wray, 2005). Moreover, interdisciplinarity in science can generate new discoveries and technologies that support the development of new research fields by branching from previous disciplines (cf., Tijssen, 2010). In the evolution of scientific fields, Small (1999, p.812) shows that: "crossover fields are frequently encountered." Finally, Sun *et al.*, (2013) state that social interaction among groups of scientists is: "the driving force behind the evolution of disciplines" (cf., Wuchty *et al.*,, 2007).

4. Laws of the evolution of science and of scientific production

- *Lotka's law of author productivity*

Lotka (1926, p. 323) claims that the frequency distribution of scientific productivity can be given by: "...the number (of authors) making *n* contributions is about $1/n^2$ of those making one; and the proportion of all contributors, that make a single contribution, is about 60 percent". Lotka (1926), using data of bibliographies in chemistry and physics, plotted in a *log-log* scale the percentage of authors making 1, 2, 3,… ,*n* contributions against the number of contributions, providing inverse square law. Lotka

(1926) used the statistical method of least-squares to compute the slope of the line that best fit the plotted data, finding that the slope was approximately -2 (cf., Potter, 1981, p.21; Coile, 1977).Potter (1981, p.36) argues that: "Lotka's law fits only a portion of the data from his 1926 study and that his most-cited figures, those for Chemical Abstracts from 1907 to 1916, do not fit his distribution...Recent studies of monograph productivity suggest that Lotka's law might reflect an underlying pattern in the behaviour of those people who produce publications, whether those publications are books or journal articles. It would appear that when the time period covered is ten years or more and the community of authors is defined broadly, author productivity approximates the frequency distribution that Lotka observed and that has become known as Lotka's law. If this is correct, then there is a universal community of all authors who have ever published whose pattern of productivity might approximate Lotka's law".

☐ *Simon-Yule law on a class of skew distribution functions*

Simon (1955) analyses a class of distribution functions that appears in a wide range of empirical data to describe sociological, biological and economic phenomena. He discusses, particularly, a number of related stochastic processes that lead to a class of highly skewed distributions (Yule distribution; Yule, 1925, 1944), possessing specific properties. In social phenomena often occur the Yule distribution. Chen (1989) argues that a difficulty in using the Lotka's law in information science is in the estimation of parameters. By contrast, Simon's modelling process for the study of Lotka's law provides significant contributions to identify a general formulation of Lotka's law. Chen *et al.*, (1994) apply a simulation algorithm based on the Simon-Yule model to conduct a computational experimentation on Lotka's law of scientific productivity, Bradford's law of bibliographic scattering, and Zipf's law of word frequency. Results suggest that the probability of a new entry can determine the characteristics of all three distributions.

☐ *Bradford's law of bibliographic scattering*

Bradford (1934, 1948) proposes a quantitative relationship between the journals and published papers. Bradford (1934) claims that: "If scientific journals are arranged in order of decreasing productivity of articles on a given subject, they may be divided into a nucleus of periodicals more particularly devoted to the subject and several groups or zones containing the same number of articles as the nucleus, then the number of periodicals in the nucleus and succeeding zones will be as 1: n: n^2.....". The graphical formulation of Bradford's law is given by plotting a curve in a plane whose coordinates are the cumulative number of articles (in the y-axis) and the logarithm of the cumulative number of journals of the collection (in the x-axis), where journals are cumulated from the most to least productive. This curve has invariably an ascending shape which, after a certain point, approaches to a straight line (cf., Garg *et al.,* 1993, pp.145*ff*). A vast literature has studied Bradford's law for a validation, for mathematical formulations of the law and applications of the law to the management of library (Vickery, 1948). Garg *et al.,* (1993) show that a Bradford's curve is obtained when scientific fields mature.

- ☐ *Zipf's law of word frequency*

Zipf's law is a fundamental model in the statistics of written and spoken natural language as well as in other communication systems (Corral *et al.,*, 2015). In particular, Zipf's law for word frequencies is one of the best known statistical regularities of language. Words occur according to a systematic frequency distribution, such that there are few very high-frequency words that account for most of the tokens in text (e.g., "a," "the," "I," etc.) and many low-frequency words. This distribution, obeying a power law called *Zipf 's law*,has: the *r*-th most frequent word with a frequency *f*(*r*) that scales according to $f(r) \propto \frac{1}{r^{a}}$

for $\alpha \approx 1$ (Zipf, 1936, 1949). In this equation, *r is* called the *frequency rank* of a word, and *f*(*r*) is its frequency in a natural corpus. Since the actual observed frequency will depend on the size of the corpus examined, this law states that: the most frequent word ($r = 1$) has a frequency proportional to 1, the second most frequent word ($r = 2$) has a frequency proportional to, the third most frequent word has a frequency proportional to, and so forth (Piantadosi, 2014). In order to explain why language obeys Zipf's law, studies should provide evidence beyond the law itself, testing assumptions and evaluating novel predictions with new and independent data (Piantadosi, 2014). Finally, Corral *et al.,* (2015) analyse several long literary texts comprising four languages, with different levels of morphological complexity. Results suggest that Zipf's law is fulfilled, i.e., a power-law distribution of word or lemma frequencies is valid for several orders of magnitude.

- ☐ *Law of cumulative advantages*

Cahlík & Jiřina (2006) propose that the evolution of scientific fields can be analysed by co-word analysis and visualized in strategic diagrams that are simulated with the law of cumulative advantages (the probability of a new tie between two keywords depends positively on the frequencies in which both keywords have taken part already). The high correspondence between simulations and evolution of real scientific fields suggests that the law of cumulative advantages can open new directions for predictions of the development of scientific fields. Cahlík & Jiřina (2006) also find that the evolution of intensity of research activity (number of publications) during the life-span of a field is correlated with some patterns of research themes concentration in a strategic diagram. Finally, Cahlík & Jiřina (2006, p.449) suggest–using co-words analysis in single periods for the evolution of themes–that: themes that live more periods often survive to further periods; themes that have had an interesting evolution survive more often than themes with simple dynamics; the themes that are central are interesting for the field and thus have a tendency to be elaborated.

- ☐ *The Matthew effect*

Merton (1968) observes that better known scientists tend to get more credit than less well known scientists for the same achievements in different fields of research, the so-called Matthew effect:

> Eminent scientists get proportionately great credit for their contributions to science while relatively unknown scientists tend to get disproportionately little credit for comparable contributions.

To put it differently, the Matthew effect is the accruing of large increments of peer recognition to scientists of great repute for particular contributions in contrast to the minimizing or withholding of such recognition for scientists who have not yet made their mark (Merton, 1988, p.609). The positive recognition by peers is the extrinsic reward in science associated with other extrinsic rewards, such as monetary income from science-connected activities, advancement in the hierarchy of scientists, and enlarged access to human and material scientific capital, derive from it. Peer recognition can be accorded only when the correctly attributed work is widely known in the pertinent scientific community. This type of extrinsic reward system provides great incentive for engaging in the challenging and hard work required to produce results that enlist the attention of qualified peers and are put to use by some of them (Merton, 1988, p.621). Moreover, Merton (1988, p.622) claims that: "Intellectual property in the scientific domain that takes the form of recognition by peers is sustained, then, by a code of common law. This provides socially patterned incentives, apart from the intrinsic interest in inquiry, for attempting do good scientific work and for giving it over to the common, wealth of science in the form of an open contribution available to all who would make use of it, just as the common law exacts the correlative obligation on the part of the users to provide the reward of peer recognition by reference to that contribution". Strevens (2006, p.168) explains three characteristics of the Matthew effect: normative negativity (an earlier unequal allocation of credit by the discoverers' contemporaries will, again, seem unjust), its absoluteness (researcher's scientific contributions are always weighted by their absolute level of eminence, whether or not there are any co-discoverers with whom to share the credit for the discovery), and its retroactive aspect (a scientist's reputation grows, their early scientific contributions are re-evaluated and reweighed by their newfound eminence, so that the credit they receive for their early discoveries increases as they become more famous). Perc (2014) argues that this effect is closely related to the concept of preferential attachment in network science, where the more connected nodes are destined to acquire many more links in the future than the auxiliary nodes. Cumulative advantage also describes the fact that advantage tends to create further advantage. In this context, Bol *et al.,* (2018) analyse data from a large academic funding program and show that winners just above the funding threshold accumulate more than twice as much funding during the subsequent eight years as nonwinners with near-identical review scores that fall just below the threshold. This effect is partly caused by nonwinners ceasing to compete for other funding opportunities, revealing a "participation" mechanism driving the Matthew effect.

□ *The economic laws of scientific research by Kealey*

Kealey (1996, p.245) proposes three laws of scientific research. Namely,

1. The first law of funding for civil research states that the percentage of national gross domestic product (GDP) spent increases with GDP per capita
2. The second law of funding for civil research states that the public and private displace each other
3. The third law of funding for civil R&D states that the public and private displacements are not equal. Public funds generate a disproportionate crowding out effect of private Research & Development (R&D) investments.

Kealey (1996) describes interesting relationships between science, technology and the economy of nations (cf., Coccia, 2005b, 2017d, 2017e, 2018e). In particular, Kealey (1996) explains that science leads to economic growth indirectly, by supporting new technologies that increase productivity in industries (Coccia, 2008, 2014b, 2018e). Higher productivity leads directly to economic growth and higher standards of living, stability of prices and economies, wellbeing and wealth of nationswith low inequality and violence in society (Coccia, 2016b, 2017c, 2017f; 2019). Kealey (1996) also argues that a high state funding does not benefit scientific development, but it can negatively impact the scientific progress (Borer, 2012; Coccia, 2017d). Overall, then, Kealey (1996) suggests that the free market produces science in a rational way— by contrast government may reduce this process. In fact, private firms can support research and technology to improve their products, whereas governments do not know what type of research should take priority (Coccia, 2005a, 2009). Government interventions can induce useless research programs for markets (Coccia, 2009). Hence, government intervention in the field of scientific research suffers from the problem of misallocating scarce economic resources: state cannot rationally allocate funding like the market does and can inhibits good research with regulations, outright research bans, etc. (cf., Coccia, 2010a, 2011) As a result, libertarian societies with a higher private investment in R&D can produce the most effective science and technology for improving wealth of nations and human welfare in society (Borer, 2012, p. 90*ff*; Coccia, 2010a; 2011, 2018c)[8].

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[8] For additional studies about science and technology, cf., Coccia, 1999, 2005, 2005a, 2005b, 2006, 2008, 2009, 2010, 2010a, 2011, 2012, 2012a, 2012b, 2012c, 2012d, 2014a, 2014b, 2015, 2015a, 2015b, 2016, 2016a, 2016b, 2017, 2017a, 2017b, 2017c, 2017d, 2017e, 2017f, 2017g; 2018, 2018a, 2018b, 2018c, 2018d, 2018e, 2018f, 2018g; 2019, 2019a, 2019b, 2019c, 2019d, 2019e, 2019f, 2019g, 2019h, 2019i, 2019l, 2019m, 2019n, 2019o, 2019p, 2019q; Coccia, 2020, 2020a, 2020b, 2020c, 2020d, 2020e, 2020f, 2020g, 2020h, 2020i; Coccia and Bellitto, 2020; Coccia and Benati, 2018, 2018a; Coccia and Bozeman, 2016; Coccia *et al.*,, 2015; Coccia and Finardi, 2012, 2013; Coccia and Rolfo, 2008, 2009; Coccia and Wang, 2015, 2016; Coccia and Watts, 2020.

6. Discussion and conclusive remarks

Seidman (1987, p.131) argues that: "Science is a mode of constructing reality in that like other symbolic constructions of the world (e.g., political ideologies, religion, aesthetic and philosophical theories) it elaborates totalizing symbolic frameworks anchored in broad philosophical theories, moral, and political views about human nature, social order, and historical development. …. Theories, in other words, become part of the cultural symbolism and meanings of a society; they orient and justify action; form elements of our personal and collective identity; and legitimate institutions and public policy. Viewing science in this manner suggests a comparable shift in our understanding of the dynamic of schools". Coccia (2019) claims that science and scientific research are driven by an organized social effort that inevitably reflects the concerns and interests of nations to achieve technical advances and discoveries to take advantage of important opportunities or to cope with environmental threats. Sun *et al.,* (2013, p. 3) show: "the correspondence between the social dynamics of scholar communities and the evolution of scientific disciplines". In general, the evolution of science is a natural process guided by curiosity, self-determination and motivation of scholars to explore the unknown in a context of social interactions between scientists, research institutions and countries in an international network of research collaborations (Adams, 2012, 2013; Coccia, 2005, 2006; Coccia, 2018, 2018d, 2019e; Coccia & Bozeman, 2016; Coccia & Wang, 2016; Gibbons *et al.,*, 1994; Newman, 2001, 2004; Pan *et al.,*, 2012). In this context, the evolution of science is due to a cumulative change based on exploration and solution of new and consequential problems in nature and society (cf., Coccia, 2016; 2017a; Scharnhorst *et al.,*, 2012; Popper, 1959). Moreover, the dynamics of science tends to follow a process that branches in different disciplines and research fields within and between basic and applied sciences (Mulkay, 1975; Coccia, 2020a). In particular, the evolution of scientific fields can be driven by convergence between applied and theoretical sciences (Coccia & Wang, 2016), new scientific paradigms (Kuhn, 1962), new research programmes (Lakatos, 1978), new technologies and breakthrough innovations (Coccia, 2016, 2017, 2017b, 2020a), fractionalization and specialization of general disciplines, etc. (Coccia, 2018, 2020a; Crane, 1972; De Solla Price, 1986; Mulkay, 1975; van Raan, 2000; Wray, 2005).

Coccia (2018), analysing the research fields of human microbiome, evolutionary robotics and astrobiology originated from a process of branching and diversification of other disciplines, suggests properties of the evolution of research fields, such as:

1) the evolution of a discipline is driven by few research fields that generate more than 80% of documents (concentration of scientific production);

2) the evolution of research fields is path-dependent of parent disciplines or new disciplines emerged with a process of scientific fission and merging;

3) the evolution of disciplines can be also due to new research fields originated from a process of specialization within applied or basic sciences and/or convergence between disciplines.

In addition, Coccia (2020a) analysing experimental physics extend the previous characteristics of science development, suggesting new properties of the dynamics of applied sciences:

a) scientific fission, the evolution of scientific disciplines generates a process of division into two or more research fields that evolve as autonomous entities creating new disciplines of scientific specialization;

b) ambidextrous drivers of science, the evolution of scientific disciplines via scientific fission is due to scientific discoveries or new technologies;

c) higher growth rates of the scientific production are in new research fields of a scientific discipline rather than old ones;

d) average duration of the growth phase of scientific production in research fields is about 80 years, almost the period of one generation of scholars.

These results are important to clarify the scientific development that can be schematically represented with different science models, as follows.

Firstly, the scientific development can be *discovery push* as in figure 2

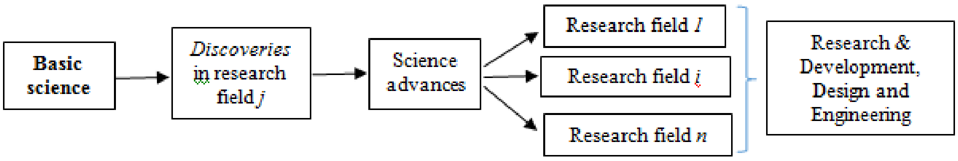

Figure 2. *Scientific development by discovery push*

Secondly, the history of science shows that scientific development can be due to new technology, i.e., *technology push* (figure 3)

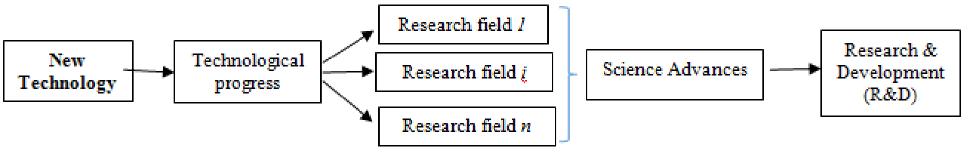

Figure 3. *Scientific development by technology push*

Thirdly, the scientific development can be also due to a solution of a problem in society or market need, as represented in the science model of *problem pull* (figure 4).

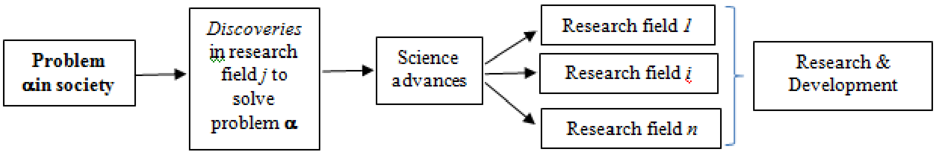

Figure 4. *Scientific development problem pull*

However, the evolution of science is more and more due to a combination among science advances, new technologies, new problems and needs in society as represented in figure 5.

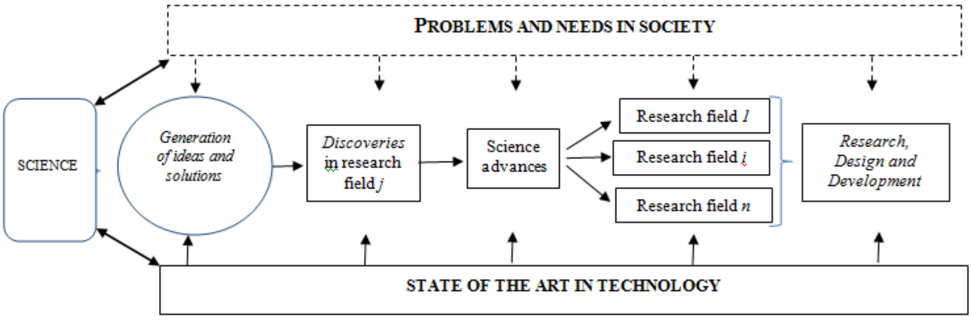

Figure 5. *Mix model of scientific development science-technology push and problem pull*

In general, the overall pattern of the scientific development is more and more due to a complex and integrated system of science, a complex network of communication paths between different research fields and technological domains, driven by interaction among scholars, labs, universities and nations linking together broader scientific and technological communities (cf., Coccia, 2018b; Coccia & Watts, 2020, Coccia, 2019g). To put it differently, the scientific development is due to a confluence of scientific and technological capabilities, market needs and problems in society within the framework of each scientific field. This new model of scientific development contains feedback loops that are sequential as in previous models, albeit with inter-functional interaction and coordination between science and technology (Fig. 6). In short, the evolution of science is due to a high level of functional interaction between science, technology and society over time and space. Hence, the scientific development is due to advances with parallel and integrated relationships between different scientific and technological domains. In fact, science and technology are more and more two integrated systems with interrelationships, such that de Solla Price (1965, p.533) in the study of science and technology stated that: "may be conceived as a pair dancers, both of whom know their steps and have an ear rhythm of the music". In this context, science system is driven by a networking process (Fig. 6). This integration and networking science system (in short, *INESS*) has the central characteristic of the use of sophisticated computer technologies and computational approaches that are enhancing the speed and efficiency of research and development across the overall system of science. For instance, the rapid development of computer technologies and applied computational science has supported computer simulation, which has a wide range of application domains in different research fields, such as molecular dynamics that applies computer simulation methods for studying the physical movements of atoms and molecules, computational fluid dynamics that uses numerical analysis and data structures to analyse and solve problems that involve fluid flows, the density functional theory based on a computational quantum mechanical modelling used in physics, chemistry and materials science to investigate atoms, molecules, and condensed phases, etc. (Coccia, 2019c, 2020a). The *INESS* involves a networks of innovators with a great variety of inputs and actors, in a world-wide connection with information and communication technologies, that support a cross fertilization of scientific and technological advances between different research fields, academic institutions and nations worldwide. This system of integration and networking in science leading to rapid scientific development is represented in figure 6.

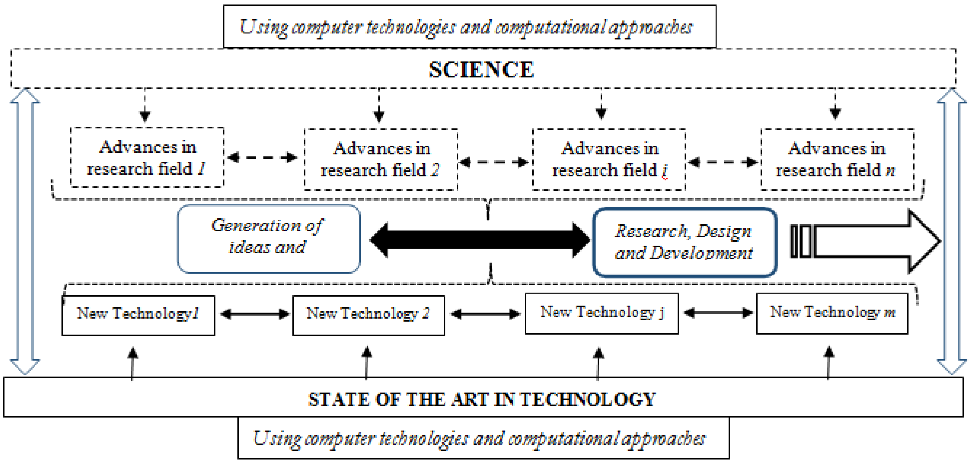

Figure 6. *Process of the scientific development by integration and networking between elements of science and technology domains.*

Overall, then, this paper here endeavours to clarify theories and laws underlying the evolution of science to improve our understanding of the functioning of science system over the course of time. This study reveals that the evolution of science is also due to manifold factors in the course of history, such as social contexts of nations, new technologies, new discoveries, economic growth, democratization of nations, military and political tensions (e.g., wars) between superpowers to prove scientific and technological superiority, new challenges between superpowers for sustaining global leadership and other events in science and society, etc. (cf., Coccia, 2010, 2011, 2015, 2017; 2018a; 2019, 2019b). As a matter of fact, the evolution of science is due to expanding human life-interests whose increasing realization constitutes progress that characterizes the human nature for millennia (Coccia & Bellitto, 2018).

However, this study here is of course tentative because we know that other things are not equal in the dynamics of science over time and space. The study here cannot be enough to explain the comprehensive characteristics of the evolution of science, because science has changed and changes rapidly similarly to culture and society. Hence, science, culture and society must be brought together in a single system to be analysed and to explain scientific development. In fact, the need of science advances has an association of social and cultural elements to cope with consequential environmental threats or to take advantage of main opportunities (cf., Ogburn & Thomas, 1922; Coccia, 2015, 2018e). Therefore, the identification and description of general patterns of the evolution of science is a non-trivial exercise. The future development of this study is to reinforce proposed results with empirical research that can further explain the evolution of applied and basic sciences for understanding how foster fruitful scientific trajectories for human progress and wellbeing in society. To conclude, for a comprehensive explanation of the evolution of science, scholars of social studies of sciences have to apply different models to capture multiple interacting levels of the science system. Hence forth, the appropriate method of inquiry in the studies of social dynamics of science has to be based on complementary multi-theoretical and multi-level approaches, rather than based on a single model/theory/hypothesis to explain this complex system in society.

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