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Disruptive innovations in quantum technologies for social change

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Abstract. The purpose of this study is the technological analysis of trajectories in quantum technologies to clarify new directions of disruptive innovations that can generate economic and social change. Patent analysis and models of time series are applied to assess the growth of quantum technologies. Findings reveals that path-breaking innovations in quantum technologies are driven by quantum information, quantum communication, quantum optics and semiconductor quantum dots. This study can explain new directions in quantum technologies to support decisions of R&D investments towards growing technological trajectories generating having a high potential impact in markets and main benefic effects in socioeconomic systems.
Keywords. Quantum technologies; Radical innovations; Disruptive innovations; Technological trajectories; Technological change; Social change.
JEL. G2, G10, F21, F68, O53, K23.

1. Introduction

Quantum technology is directed to transmission and manipulation of quantum bits (*or* qubits)[1] and has a high potential of improving information processing and communication between remote locations (Kozlowski & Wehner, 2019; Long *et al.*, 2019). Quantum technology is at the initial stage of evolution but in future it will greatly support new computational approaches to model and operationalize rules in algorithmic form to solve complex problems in society (Atik & Jeutner, 2021; Carberry *et al.*, 2021). Principal firms, such as Intel and IBM, are increasing their R&D investments in these critical research fields and technologies (Coccia, 2017a, 2017b; Möller & Vuik, 2017). Quantum research and technology is developing manifold trajectories to improve the solution of complex problems and/or the satisfaction of needs in society, such as quantum cryptography and communications, entanglement and discord, quantum algorithms, quantum error correction and fault tolerance, quantum computer science, quantum imaging and sensing, experimental platforms for quantum information, etc. (Dahlberg *et al.*, 2019). The evolution of this technology needs time, R&D investments, selected research policy, strategic decisions of firms and nations, etc. to support a complete and functional quantum ecosystem, based on reliable physical infrastructures, human

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[1] Qubits in the quantum mechanical are the analogue of classical bits.

resources high-skilled and appropriate technological systems to deal with and solve societal problems (cf., Coccia, 2017, 2017c, 2018a; Hou & Shi, 2021; Granstrand & Holgersson, 2020; Oh *et al*., 2016). In addition, the evolution of quantum science requires interdisciplinarity approaches, different know-how and converging technologies from physics, chemistry, operating systems, computer science, artificial intelligence, nanotechnology, computer networks, etc. to support scientific and technological development of quantum computing and information (Kozlowski & Wehner, 2019). Current quantum research is proposing new approaches and applications, such as algorithms to accelerate quantum machine learning over classical computer algorithms (Pande & Mulay, 2020; Rao *et al*., 2020), techniques and tools for drug discovery (Batra *et al*., 2021), preliminary approaches of cryptography, etc. There is a vast literature in these research fields, however, which research fields and technological trajectories in quantum computing are supporting the evolution of quantum science and technology are hardly known. This study confronts these problems here by developing a statistical analysis based on data of publications and patents to explain the evolution of emerging research and technological trajectories in quantum research. The balance of the paper proceeds as follows. First, we describe a theoretical framework of this study underpinned in the economics of technology. Second, we present data and methodology used to analyze data and detect scientific and technological trajectories that can explain the evolution of quantum science over time. We then show relevant findings; discussions and conclusion show how the evolution of quantum science and technology proceeds to provide theoretical and innovation management implications.

2. Theoretical framework of economics of innovation

The evolution of technologies is driven by science that is often viewed as a self-organizing system based on various scientific and social changes (Börner, 2011; Sun *et al*., 2013)[2]. Scholars maintain that the evolution of technologies is driven by the interaction between inter-related technological systems and scientific fields that generate co-evolutionary pathways and technological change (Benamar *et al*., 2020; Coccia & Watts, 2020; Coccia *et al*., 2021; Jovanovic *et al*., 2021). Quantum technology has many characteristics of general-purpose technologies (GPTs) because it has the potential to make prior technical knowledge obsolete and sustain technological, industrial, economic and social change (Sahal, 1981; Bresnahan, 2010). The technological aspects of GPT are basic to analyze and explain the quantum technology, and some brief background is useful to understand and clarify this vital concept for technology analysis here. GPTs are enabling technologies that support clusters of new products and

[2] For role of science and technology in economic and social change see: Ardito *et al*., 2021; Calabrese *et al*., 2005; Coccia, 2003, 2005a, 2005b; Coccia, 2008, 2014, 2015, 2015a, 2016, 2017a, 2018b, 2018c, 2018d, 2019, 2019a, 2019b, 2019c, 2019d, 2019h, 2021l; Coccia & Cadario, 2014; Coccia & Finardi, 2012, 2013; Coccia & Rolfo, 2000, 2008; Coccia & Watts, 2020; Pagliaro & Coccia, 2021.

processes (Helpman, 1998, p.3; cf., Calabrese *et al.*, 2005). GPTs generate changes of techno-economic paradigms, which affect every branch of the economy and sustain the long-run process of economic growth in human society (Freeman & Soete, 1987, pp.56–57; Bresnahan & Trajtenberg, 1995, p.8)[3]. These path-breaking innovations are of transformative nature and generate a destructive creation, which makes prior products/processes and knowledge obsolete (Calvano, 2007). Lipsey *et al.* (1998, p.43) define a GPT as: "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." Moreover, GPTs exert a pervasive impact across firms, industries and permeate the overall economy and society of nations (Coccia, 2020). GPTs are revolutionary innovations that generate several ripples of techno-economic effects that change the structure of firms, industries, and society (Peirce, 1974). 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." In fact, GPTs generate clusters of innovations in several industries because they support basic processes/components/technical systems for the architecture of various families of products/processes that are made quite differently. In general, GPTs are characterized by: "pervasiveness, inherent potential for technical improvements and 'innovational complementarities', giving rise to increasing returns-to-scale, such as steam engine, electric motor, and semiconductors" (Bresnahan & Trajtenberg, 1995, p.83). Jovanovic & Rousseau (2005, p.1185) show the distinguishing characteristics of a GPT:

1. *Pervasiveness:* GPT should propagate to many sectors
2. *Improvement:* GPT should reduce costs of its adopters
3. *Innovation spawning:* GPT should produce new products and

processes (cf. also, Bresnahan & Trajtenberg, 1995).

Lipsey *et al.* (1998, p.38ff) describe other similar characteristics of GPTs, such as: the scope for improvement, wide variety, and range of uses and strong complementarities with existing or potential new technologies (cf., Coccia, 2020). Another feature of GPTs is a long-run period between their initial research, the emergence as invention and final introduction in new products/processes having a societal impact (Lipsey *et al.*, 1998, 2005).

[3] cf., Hall & Rosenberg, 2010; Lipsey *et al.*, 1998; Li, 2015; Ruttan, 1997; Schultz & Joutz, 2010; von Hippel, 1988.

Rosegger (1980, p.198) showed that the estimated time interval between invention and major innovation can be about 50 years: e.g., for electric motor is about 58 years, electric arc lights 50 years, telegraph about 44 years, synthetic resins 52 years, etc. Overall, then, GPTs are complex technologies that support product/process innovations in several sectors for a corporate, industrial, economic, and social change (Coccia, 2015, 2017d, 2017e, 2020). The characteristics of GPTs can help the explanation of scientific and technological development of quantum science and technology. In particular, the technology analysis of new trajectories of quantum technology is essential to predict technological and social change. Nelson (2008, p.489) claims that:

> scientific understanding underlying a technology tends to be contained in the applications-oriented sciences… a strong body of scientific understanding enables technological progress to be rapid and sustained… the research in the engineering disciplines and applications-oriented sciences aims to develop an understanding of what is going on in the operation of the relevant field of practice, so as to illuminate how to advance it.

The quantum technology as a complex technology can generate "certain meta-evolutionary processes involving a combination of two or more symbiotic technologies whereby the integrated system structure is drastically simplified" (Sahal, 1985, p.70, original emphasis). Nelson (2008) also argues that the evolutionary growth of complex technologies is due to a process of learning based on the ability to identify, control, and replicate practices (von Tunzelmann *et al.*, 2008, p.479; cf. also Nelson, 2008, p.488). Sahal (1985, p.79, original emphasis) maintains that: "the process of technological evolution is characterized not only by specific innovation avenues that concern individual industries…, but generic innovation avenues as well, that cut across several industries... it is apparent that the emergence of a new innovation avenue through fusion of two or more avenues or through fission of an existing avenue can give rise to sudden changes in the mode and tempo of technical progress". The goal of investigating here technological trajectories of quantum technology and science is important to clarify how the long-run evolution of this technology depends on the behavior and evolution of different inter-related technologies, i.e., the long-run evolution of technology can be due to interlocking and positive feedbacks between technologies. Hence, the detection of emerging research fields and technology in quantum science can provide main characteristics to understand future evolutionary paths in science and society (Deshmukh & Mulay, 2021). In this context, the study here analyzes publications and patents that are a main unit of scientific and technology analysis to show how scientific fields and technological trajectories evolve over time (Boyack *et al.*, 2009; Jaffe & Trajtenberg, 2002). As matter of fact, quantitative approaches based on bibliometric data of journals are useful techniques to capture information earlier in the cycle of technology development, whereas patents, in contrast, trail behind (Cozzens *et al.*, 2010; Ding *et al.*, 2000). Arora *et al.* (2013) apply a bibliometric analysis of publication metadata to investigate emerging nanotechnology research and innovation (cf., Chen, 2006). Van den Oord & van Witteloostuijn (2018) develop a multi-level model to study the evolution of emerging biotechnology. In this research stream, the study here has the purpose of detecting emerging technology in quantum science. The idea here is to analyze the evolution of quantum science by examining new technological trajectories that are basic in science, technology, and society. Next section presents the methods of this scientific investigation (cf., Coccia, 2018).

3. Study design

3.1. Sources and sample

The study uses Scopus (2021) data, a multidisciplinary database covering journal articles, conference proceedings, and books. Scopus (2021) database also includes patent records derived from five patent offices (the US Patent & Trademark Office, the European Patent Office, the Japan Patent Office, the World Intellectual Property Organization, and the UK Intellectual Property Office). In particular, the window of "Search documents" in the Scopus (2021) database is used to identify scientific documents having in article title, abstract or keywords the term "quantum computing" and "quantum computer". Scientific products (articles, conference papers, conference reviews, book chapters, short surveys, letters, etc.) and patents are the basic units for technology and scientific analyses that explain the evolution of science and technology in the field of quantum research under study here (Ding *et al.*, 2000; Glänzel & Thijs, 2012; Savov *et al.*, 2020).

3.2. Measures

For scientific development, scientific products detect the evolution of quantum research:

– Number of articles and all scientific products in "quantum computing", 10,089 document results over 1989-2020 period (downloaded on November 22, 2021; the year 2021 is excluded because ongoing).

– Number of articles and all scientific products in "quantum computer", 19,266 document results over 1967-2020 period (downloaded on November 22, 2021; the year 2021 is also here excluded because ongoing).

For technology analysis, patents indicate inventions and show the potential evolution of quantum technology:

– Number of patents in "quantum computing", 8,505 patents over 1977-2020 period (downloaded on November 22, 2021; the year 2021 is excluded because ongoing).

– Number of patents in "quantum computer", 9,792 patents over 1985-2020 period (downloaded on November 22, 2021; the year 2021 is excluded because ongoing).

3.3. Specification of the model and data analysis procedure

The tool "Search documents" in Scopus (2021, 2021a) provides a time series of document results and keywords with the highest number of documents in quantum research, given by:

- Quantum Optics
- Qubits
- Quantum Entanglement
- Quantum Algorithms
- Quantum Electronics
- Quantum Cryptography
- Semiconductor Quantum Dots
- Quantum Information
- Quantum Computation
- Quantum Communication
- Quantum Circuit

Each of this keyword is inserted in the window "search documents" to detect the specific time series of related research fields or technologies that are used to detect the growth of research fields and technologies for a comparative analysis within quantum science.

The study applies some models for scientific and technology analysis in quantum science.

Firstly, trends of research field/technology i at t are analyzed with the following model:

$$Log\ y_{i,t} = a + b\ time + u_{i,t} \quad (1)$$

a is a constant; log has base e= 2.7182818; t=time; u_t= error term

y_t is scientific products *or* patents

Secondly, the evolution of technology of quantum computing and quantum computer is analyzed with the model of technological evolution by Sahal (1981) in which the number of patents (Y) is a function of the number of scientific production (X), i.e., Y=f(X) considering X and Y two basic elements of the technological system in quantum computer or quantum computing. This model provides the relative rate of growth to show if the evolution of technology in Quantum science has a pathway of development, growth or under-development. The details of this model are described in Appendix A.

The relationships of models under study here for scientific and technology analysis are investigated using the Ordinary Least Squares (OLS) method for estimating the unknown parameters in regression models. Statistical analyses are performed with the IBM SPSS Statistics 26®.

4. Results of empirical analyses on trajectories in quantum technology

First, data are transformed in logarithmic scale to have normality in the distribution of variables for appropriate parametric analyses applied here.

4.1. Growth of research fields in quantum science

Table 1. *Estimated relationships of scientific production in quantum research as a function of time*

Dependent variable: scientific products concerning scientific fields in quantum research					
Research fields	*Coefficient* b_1	*Constant a*	*F*	R^2	*Period*
Quantum Optics, *Log* $y_{i,t}$	.082***	−157.17**	13.99***	.37	*(1958-2020)*
Qubits, *Log* $y_{i,t}$	.204***	−403.64***	36.05***	.60	*(1983-2020)*
Quantum Entanglement, *Log* $y_{i,t}$	.168***	−332.13***	40.61***	.63	*(1990-2020)*
Quantum Algorithms, *Log* $y_{i,t}$	.122***	−241.68***	15.02***	.39	*(1970-2020)*
Quantum Electronics, *Log* $y_{i,t}$	−.020	45.25	.184	.008	*(1959-2020)*
Quantum Cryptography, *Log* $y_{i,t}$	.121***	−238.09***	19.41***	.45	*(1983-2020)*
Semiconductor Quantum Dots, *Log* $y_{i,t}$	.156***	−305.64***	24.71***	.51	*(1987-2020)*
Quantum Information, *Log* $y_{i,t}$	.173***	−342.32***	24.31***	.51	*(1975-2020)*
Quantum Computation, *Log* $y_{i,t}$	.114**	−223.53**	11.66***	.33	*(1952-2020)*
Quantum Communication, *Log* $y_{i,t}$	.127***	−249.95***	20.36***	.46	*(1965-2020)*
Quantum Circuit, *Log* $y_{i,t}$	.119***	−234.06***	15.55***	.39	*(1976-2020)*

Note: Explanatory variable is *time in years*. Period in the last column: the first year indicates the first paper recorded, the second year is 2020 because 2021 is still ongoing.
*** significant at 1‰; ** significant at 1%. *F* is the ratio of the variance explained by the model to the unexplained variance
R^2 is the coefficient of determination.

Table 2. *Estimated relationships of patents in quantum science as a function of time*

Dependent variable: Patents in quantum science

Research fields	*Coefficient* b_1	*Constant a*	*F*	R^2	*Period*
Quantum Optics, *Log* $y_{i,t}$	.092***	−180.88***	99.71***	.83	*(1977-2020)*
Qubits, *Log* $y_{i,t}$	.237***	−471.43***	221.44***	.91	*(1924-2020)*
Quantum Entanglement, *Log* $y_{i,t}$	.174***	−346.48***	91.55***	.81	*(1987-2020)*
Quantum Algorithms, *Log* $y_{i,t}$	.164***	−326.77***	73.97***	.78	*(1983-2020)*
Quantum Electronics, *Log* $y_{i,t}$	−.005	15.67	.340	.016	*(1963-2020)*
Quantum Cryptography, *Log* $y_{i,t}$	.117***	−230.29***	37.56***	.64	*(1990-2020)*
Semiconductor Quantum Dots, *Log* $y_{i,t}$	.121***	−237.01***	102.07***	.83	*(1988-2020)*
Quantum Information, *Log* $y_{i,t}$	.177**	−351.63***	90.81***	.81	*(1983-2020)*
Quantum Computation, *Log* $y_{i,t}$	.164***	−324.22**	73.43***	.78	*(1990-2020)*
Quantum Communication, *Log* $y_{i,t}$	.170***	−337.00***	77.12***	.79	*(1984-2020)*
Quantum Circuit, *Log* $y_{i,t}$	.175***	−348.09***	159.97***	.88	*(1949-2020)*
Quantum Linguistics, *Log* $y_{i,t}$	.094***	−182.84***	189.55***	.90	*(1986-2020)*

Note: Explanatory variable is *time in years*. Period in the last column: the first year indicates the first paper recorded, the second year is 2020 because 2021 is still ongoing.
*** significant at 1‰
F is the ratio of the variance explained by the model to the unexplained variance
R^2 is the coefficient of determination

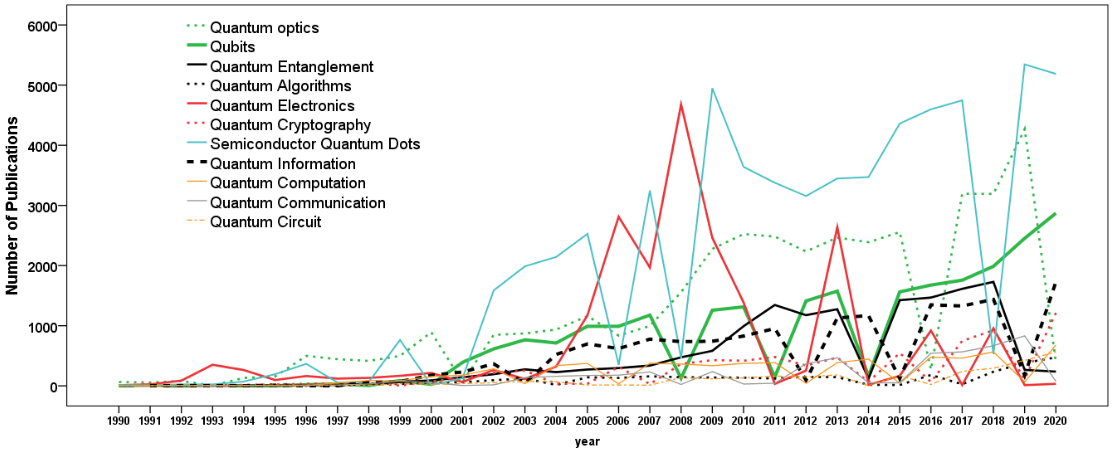

Figure 1. *Trends of research fields in quantum research using scientific production.*
Note: to show better the trends the period starts from 1990

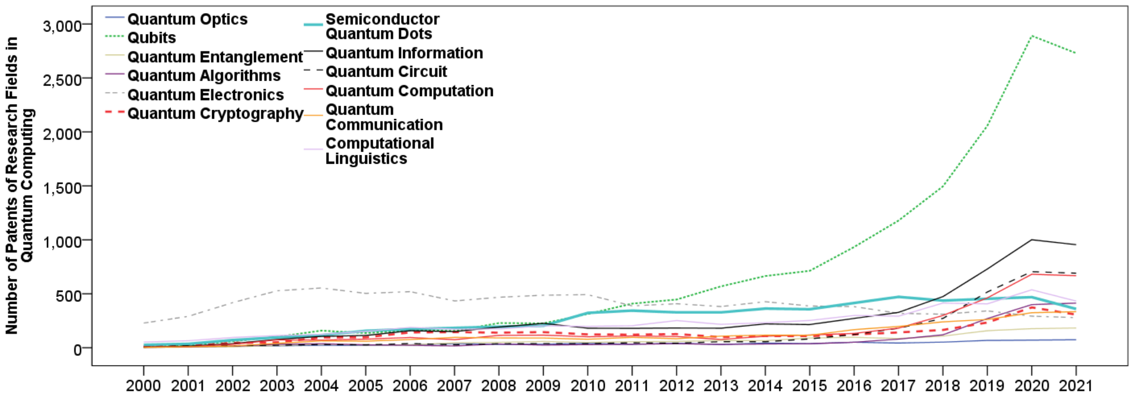

Figure 2. Technological trajectories in quantum science using patents.
Note: to show better the trends the period starts from 2000

Table 3. *Evolutionary growth of scientific fields and technological trajectories in quantum science based on coefficients of regression of table 1 and 2, and their scientific age from the first scientific products to year 2020*

Research fields	Coefficient of Publication	Age	Research fields	Coefficient of patents	Age
Qubits	0.204	37	Qubits	0.237	96
Quantum Information	0.173	45	Quantum Information	0.177	37
Quantum Entanglement	0.168	30	Quantum Circuit	0.175	71
Semiconductor Quantum Dots	0.156	33	Quantum Entanglement	0.174	33
Quantum Communication	0.127	55	Quantum Communication	0.170	36
Quantum Algorithms	0.122	50	Quantum Algorithms	0.164	37
Quantum Cryptography	0.121	37	Quantum Computation	0.164	30
Quantum Circuit	0.119	44	Semiconductor Quantum Dots	0.121	32
Quantum Computation	0.114	68	Quantum Cryptography	0.117	30
Quantum Optics	0.082	62	Quantum Optics	0.092	43
Quantum Electronics	not significant		Quantum Electronics	not significant	96

Table 3, using the coefficient of regression of models calculated in table 1 and 2 (trends are displayed in Figure 1 and 2), reveals research fields and technological trajectories having a high rate of growth in quantum science, given by:

- o Qubits
- o Quantum information
- o Quantum entanglement (publications)
- o Quantum circuit (patents)
- o Quantum communication
- o Quantum algorithms and quantum cryptography (publications)

Macroevolution of technology in quantum computer and quantum computing is in table 4. Results show that the evolution of technology in quantum computing and quantum computer, having B>1 (see Appendix A for details) has a disproportionate growth over time, suggesting that it can generate a technological paradigm shift affecting future economic and social change.

Table 4. *Parametric estimates of the model of technological evolution*

Research fields	Estimated relationship			Period
Quantum computing	log Y=	−1.117	+1.084logX	
		(0.448)	(.084)	
		p<0.001	p<0.05	
	R^2=0.851	S=0.965	F=165.514***	(1985-2021)
Quantum computer	log Y′=	−2.366	+1.215logX′	
		(0.454)	(.076)	
		p<0.001	p<0.001	
	R^2=0.901	S=0.751	F=253.764***	(1985-2021)

Note: Y = Patents of quantum computing (Y) or quantum computer (Y′); X= publications in quantum computing, (X′) publications in quantum computer (explanatory variables); The standard errors of the regression coefficients are given in parentheses. p is the p-value. R^2 is the coefficient of determination, S the standard error of the estimate. F the ratio of the variance explained by the model to the unexplained variance.

5. Discussions

The evolution of quantum science over the last decades is unparalleled (Scheidsteger *et al*., 2021). Studies show that quantum science has four main pathways, that of course are not exhaustive: (i) quantum information science; (ii) quantum sensing, imaging, and control; (iii) quantum communication and cryptography; and (iv) quantum computation (cf., Dowling, & Milburn, 2003; Jaeger, 2018; Long *et al*., 2019). To develop this research stream with new data and technology analysis, this study shows main scientific and technological trajectories in the evolution of quantum science over time, given by Qubits, Quantum information, Quantum entanglement, Quantum circuit, Quantum communication, Quantum algorithms and quantum cryptography. These new directions in quantum science that can generate a tectonic shift of scientific and technological progress that will affect economic and social change in future human society.

The explanation of these emerging trajectories can clarify their potential for a revolutionary shift in science and technology:

- Qubits. In classical computing the information is encoded in bits that exist in one of two states: a 0 or a 1. In quantum computing the information is encoded in quantum bits, or qubits, which can exist in superposition (it can be 0 and 1 at the same time). Qubits represent atoms, ions, photons or electrons and their respective control devices that work together to act as computer memory and a processor. Quantum computer can contain these multiple states simultaneously and has the potential to be more powerful than current most powerful supercomputers. Qubits have main applications in physically realized photonic, atomic and solid-state systems, quantum memories, etc. (de Brugière *et al.*, 2022).

- Quantum information is the information of the state of a quantum system. Quantum information science is an interdisciplinary field that seeks to understand the analysis, processing, and transmission of information using principles of quantum mechanics. Quantum information can solve problems and perform data processing using a quantum system as the information carrier, rather than binary '1's and '0's used in conventional computation. Quantum information is developing the technology and exploring applications on multiple fronts, such as atomic clocks potentially could be used as quantum sensors. These quantum logic clocks are part of a new generation of ultraprecise timekeeping devices that can also act as sensors of gravity (Wineland *et al.*, 2002). Quantum communication is also one of the applications of quantum information. Another main application is quantum teleportation: quantum information gets instantly transferred from one qubit to another (NIST, 2021).

- Quantum entanglement is a physical phenomenon that occurs when a group of particles are generated, interact, or share spatial proximity in a way that the quantum state of each particle of the group cannot be described independently of the state of the others, including when the particles are separated by a large distance. To put it differently, quantum entanglement is a state where two systems (a system is usually an electron or photon) are so strongly correlated that the obtaining of information about one system's "state" will give immediate information about the other system's "state", though they are apart these systems (Zou *et al.*, 2021). Quantum entanglement has been demonstrated experimentally with photons and neutrinos (Kocher & Commins, 1967), electrons (Hensen *et al.*, 2015); molecules (Arndt *et al.*, 1999; Nairz *et al.*, 2003), small diamonds (Lee *et al.*, 2011) etc. In addition, the utilization of entanglement in communication, computation and quantum radar are very active areas of research and development. Entanglement can enable quantum cryptography and superdense coding to be faster than light speed communication, and even teleportation, though current problems with quantum computers about time and processing power-consuming.

- Quantum circuit, in quantum information theory, is a model for quantum computation; a quantum circuit is a computational routine consisting of coherent quantum operations on quantum data, such as qubits. Any quantum program can be represented by a sequence of quantum circuits and non-concurrent classical computation (cf., Ovalle-Magallanes *et al.*, 2022)

- A classical (or non-quantum) algorithm is a finite sequence of instructions, or a step-by-step procedure for solving a problem, where each step or instruction can be performed on a classical computer. Similarly, a quantum algorithm is a step-by-step procedure, where each of the steps can be performed on a quantum computer. Quantum algorithms use some essential feature of quantum computation, and they can solve some problems faster than classical algorithms by technological aspects of quantum superposition and quantum entanglement (Lanzagorta *et al.*, 2009; Nielsen & Chuang, 2010; Shao *et al.*, 2019).

- Communication is one of the most promising research fields of quantum physics closely related to important works, such as quantum teleportation, quantum information processing and quantum cryptography. The last one turns to be the most interesting application which aims to protect information channels against eavesdropping by means of quantum cryptography. In fact, the most well-known and developed application of quantum cryptography is quantum key distribution: it describes the use of quantum mechanical effects to perform cryptographic tasks or to break cryptographic systems. One critical component of all proper encryption schemes is true randomness which can be generated by means of quantum optics (Bennett *et al.*, 1992).

- Quantum cryptography will lead to the final solution for cyberattacks and for this reason many efforts have been dedicated to this growing field of research. The advantage of quantum cryptography lies in the fact that it allows the completion of various cryptographic tasks that are proven or conjectured to be impossible, such as, it is impossible to copy data encoded in a quantum state. In the presence of an attempt to read the encoded data, the quantum state will be changed due to wave function collapse. This approach could be used to detect eavesdropping in quantum key distribution (Bennett *et al.*, 1992; Chen *et al.*, 2015). Cloud computing and e-commerce can be growing areas by applying quantum computation. Current limitations are due to very large and expensive computers capable to transmitting information using quantum cryptography. Moreover, now there is no algorithm efficient enough to do the factoring quickly, but future technological development could eventually find it. In short, quantum cryptography is a true breakthrough in the field, though we need time for creating learning processes for reliable applications of this technique in practical problems in society.

These findings and discussions show that quantum science is evolving with endogenous processes of interaction between different research fields and technologies, just described, that increase the size and complexity of the ecosystem of quantum science driving scientific and technological change.

6. Concluding remarks

Quantum science can support the answer to questions in science and society that need a lot of data; as consequence, quantum technology, as a general-purpose technology, can have main applications in manifold fields and as the technology develops, the more uses we will find for it. The evolution of quantum science shows that new research fields and technologies are growing (e.g., qubits, quantum information and algorithms, quantum communication, etc.) to support the emergence of ecosystem based on a complex network of interconnected systems including scholars, academic institutions, collaborations, financial resources, etc. (Coccia, 2019c, 2019d, 2019e, 2019f, 2019g, 2020d, 2020e, 2020f, 2020g, 2020h, 2021i, Coccia & Bellitto, 2018; Coccia & Benati, 2018; Coccia and Cadario, 2014; Coccia & Finardi, 2012, 2013; Coccia & Rolfo, 2000, 2008)[4]. Results also reveal that quantum computing research and technologies are evolving, more and more, with a transition from hardware to software aspects represented by growing trajectories of quantum information and quantum algorithms (cf., Li *et al*., 2021).

These results bring us to conclusions that are, of course, tentative. Although this study has provided some interesting, albeit preliminary results, as many other bibliometric studies, it has several limitations. First, the precision of the search queries is affected by ambivalent meanings in quantum computing, such as information, computing, computer, etc. Second limitation of this study is that sources understudy may only capture certain aspects of the ongoing dynamics of quantum science and technology. Third, there are multiple confounding factors that could have a significant role in the dynamics of quantum research to be further investigated, such as R&D investments, collaboration intensity, openness, intellectual property rights, etc. Fourth, quantum research and technology change their borders during the evolution of science, such that the identification of stable technological trajectories and new patterns in the evolutionary dynamics is a non-trivial exercise.

Despite these limitations, the results presented here clearly illustrate critical technological trajectories in quantum science and technology. The description of evolutionary pathways in quantum science here can improve the allocation of R&D investments towards private and public organizations involved in vital research fields for increasing beneficial social impact. In fact, the explanation of the evolution of quantum technologies can provide main information having numerous implications for decision making of policymakers and funding agencies regarding sponsoring specific research fields and technological trajectories in quantum science that can accelerate the development of science and technology (Roshani *et al*., 2021). This study

[4] An interesting case of emerging ecosystem associated with a new research field is based on studies concerning COVID-19 Pandemic that is generating a lot of scientific and technology change in different areas of life science and not only (cf., Coccia 2018f, 2020a, 2020b, 2020c, 2020i, 2020l; Coccia, 2021, 2021a, 2021b, 2021c, 2021d, 2021e, 2021f, 2021g, 2021h, 2021i, 2022, 2022a).

shows critical research fields and technologies in quantum computing that are growing, and policy makers can allocate economic resources towards these research fields and technologies (e.g., quantum information, quantum cryptography, etc.) to foster the development of new knowledge, scientific research, and technologies for positive impact in science and society.

However, future research should consider new data when available, and when possible, apply new approaches to reinforce proposed results directed to explain the evolution of quantum science and technology. The future development of this study is also directed to design indices of technometrics to assess and predict the evolution of new technological trajectories in quantum research and technologies, as well as to support further implications for management of technology and industrial change. To conclude, the results presented here clearly illustrate the need for more detailed examination of technology analysis to clarify the structure and evolution of quantum research, supporting appropriate strategies of research policy that accelerate the development of quantum science and technology with fruitful effects for the current and future wellbeing of people in society.

Appendix

Model of technological evolution

To operationalize the technology analysis of quantum computing directed to measure, assess and predict technological trajectories, this study proposes a simple model of technological evolution by Sahal (2021). This model measures the effect that production of publications has on patents' growth within the field of research, considering publication and patents as elements of the same scientific system. This approach was originated to study biological principles of allometry and subsequently applied in economics of technology to analyze the patterns of technological innovation (Sahal, 1981).

The general model is based on following assumptions.

(1) Suppose the simplest possible case of only two elements, X (publications) and Y (patents), forming a system in a specific scientific and technological domain.

(2) Let $Y(t)$ be the extent of advances of a technology Y at the time t and $X(t)$ be the extent of scientific production underlying the advances of a technology Y. Suppose that both X and Y evolve according to some S-shaped pattern, such a pattern can be represented analytically in terms of the differential equation of logistic function. For X, scientific production, the starting equation is:

$$\frac{1}{X}\frac{dX}{dt} = \frac{b_1}{K_1}(K_1 - X)$$

The equation can be rewritten as:

$$\frac{K_1}{X}\frac{1}{(K_1 - X)}dX = b_1 dt$$

The integral of this equation is:

$$log\,X - log(K_1 - X) = A \quad + b_1 t$$

$$log\frac{K_1 - X}{X} = a_1 - b_1 t$$

$$X = \frac{K_1}{1 + exp(a_1 - b_1 t)}$$

$a_1 = b_1 t$ and t = abscissa of the point of inflection.

The growth of $X(t)$ can be described respectively as:

$$log\frac{K_1 - X}{X} = a_1 - b_1 t \qquad (1)$$

Mutatis mutandis, for Patents $Y(t)$ the equation is:

$$log\frac{K_2 - Y}{Y} = a_2 - b_2 t \qquad (2)$$

The logistic curve here is a symmetrical S-shaped curve with a point of inflection at 0.5K with $a_{1,2}$ are constants depending on the initial conditions, $K_{1,2}$ are equilibrium levels of growth, and $b_{1,2}$ are rate-of-growth parameters (1=Publications, 2=Patents).

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

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

The expression generated is:

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

Equation [3] in a simplified form is $C_1 = exp[b_1(t_2 - t_1)]$ with $a_1 = b_1 t_1$ and $a_2 = b_2 t_2$ (cf. Eqs. [1] and [2]).

The model of technological evolution is given by:

$$Y = A \quad (X)^B \qquad (4)$$

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

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

$$log\,Y = log\,A + B \quad log\,X \tag{5}$$

B is the evolutionary coefficient of growth that measures the evolution of technology Y in relation to scientific production X.

This model [5] has linear parameters that are estimated with the Ordinary Least-Squares Method. The value of $B \gtrless 1$ in the model [5] measures the relative growth of Y in relation to the growth of X and it indicates different patterns of technological evolution: B<1 (underdevelopment), B ≥ 1 (growth or development of technology). In particular,

- $B<1$, whether technology Y evolves at a lower relative rate of change than X; the whole system has a slowed evolution (*underdevelopment*) over the course of time.

- B has a unit value: $B = 1$, then Y and X have proportional change during their evolution. In short, when B=1, the whole system here has a proportional evolution (*growth*).

- $B>1$, whether Y evolves at greater relative rate of change than X; this pattern denotes disproportionate advances. The whole system of technology Y has an accelerated evolution (*development*) over the course of time.

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