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Article

Dynamics of Converging Scientific and Technological Development in Artificial Intelligence and Quantum Technologies

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Abstract: Artificial intelligence and Quantum science supports path-breaking technologies for main technological change. The investigation goal of this study is to examine their scientific and technological development to explain drivers of these disruptive technologies. Analyses of data, based on publications and patents in quantum science and artificial intelligence, with a technometric model show that that quantum science and technology has a growth rate of 1.07, artificial Intelligence ha a rate of growth of 1.37, whereas the interaction of quantum science and artificial intelligence generates a convergent technological trajectory that has an accelerated rate of growth of 1.58, higher than trends of these technologies taken individually. These findings here clarify one of the fundamental determinants of the evolution of path-breaking technologies that can support decision making of policymakers, technology analysts and R&D managers to direct R&D investments towards fruitful inter-relationships between radical technologies that foster scientific and technological change in knowledge economies.

Keywords: quantum technologies; artificial intelligence; technological trajectories; R&D management; converging technologies; technological interaction; technological evolution; technometrics; technological advances

1. Introduction and Investigation Goal

One of the fundamental problems in science is how a scientific field and related technology emerge and sustain radical scientific and technological change (Arthur, 2009; Coccia, 2021; Fortunato et al., 2018; Kuhn, 1962; Lakatos et al., 1980; Price, 1986; Scharnhorst et al., 2012). The evolution of new research fields and technologies, such as ICTs, nanotechnology, quantum computing, etc. generates converging processes with unparalleled effects in science and society (Coccia, 2012, 2022; Sun et al., 2013).

In this context, this paper here endeavors to analyze the interaction between research fields and path-breaking technologies to assess patterns of growth that are basic for scientific and technological change. The development of this study flows from a recognition that research scientists have performed less well in the understanding of how and why certain scientific fields and technologies interact in regimes of rapid change (Sun et al., 2013). Many theories of scientific development have been inspired by Kuhn (1962) with the notion of paradigm shifts and Lakatos (1980) with the management of research program. Some theory of science development explains the evolution of fields to branching mechanisms, caused by evolutionary growth and new discoveries (Coccia, 2020, 2022a; Mulkay, 1975), specialization or merging of different research fields (Coccia, 2018; Coccia et al., 2022, 2024). Other models focus on the synthesis of elements of preexisting disciplines (Noyons and van Raan, 1998). All of these models point to the self-organizing development of science exhibiting growth and interaction between inter-related research fields measured with co-citations in publications (van Raan, 1990). Studies also shows that the evolution of research fields is guided by the social interactions among scientists with an invisible college (Crane, 1972; Sun et al., 2013; Wagner, 2008).

Although the vast literature, quantitative works on the interaction between emerging research fields and technologies are lacking to date. In particular, how the interaction of research fields can affect patterns of growth is a topic hardly known in science. This paper endeavors to analyze one of the driving forces that may support the symbiotic co-evolution of research fields and emergence of a new technological regime, given by interaction between research fields and technologies that can affect inter-related pathways of growth and generate scientific and social change. In particular, this study confronts the problem here by developing a statistical analysis that focuses on two emerging research fields and technologies given by artificial intelligence, in short AI (the application of computer systems to mimic the problem-solving and decision-making capabilities of the human mind; Coccia, 2020) and quantum science that applies the principles of quantum mechanics –the physics of sub-atomic particles– and has the potential to improve computing and communication technologies with manifold applications in different environments (Acín et al., 2018; Arute et al., 2019; Burger et al., 2023; Cushing and Osti, 2023; Dhamija and Bag, 2020, Thew et al., 2020). The study is based on a large dataset of publications and patents for technometric analyses to show how these research fields and new technologies evolve independently and, in their interaction, to clarify the evolutionary behaviour that can explain scientific and technological change (Cozzens et al., 2010; Scheidsteger et al., 2021). This study is especially relevant in a knowledge-based world to clarify the interaction between research fields and technologies having a high potential of growth to support next industrial and economic change.

2. Materials and Methods

2.1. Sources and Sample of Data

The study uses data of Scopus (2023), a multidisciplinary database covering journal articles, conference proceedings, letters, book chapters and books. Scopus (2023) database also includes patent records from different patent offices worldwide. The window of "Search documents" in the Scopus (2023) database is used to identify scientific documents and patents having in article title, abstract or keywords the following terms from starting year until July 2023 (when data are downloaded):

("quantum technology"), number of publications: 3,989; number of patents: 6,302, from 1988 to 2022 period

("artificial intelligence"), number of publications: 463,512; number of patents: 239,210, from 1960 to 2022 period

combined search: ("quantum" and "artificial intelligence"), number of publications: 60; number of patents: 447, from 2004 to 2022 period. This combination with Boolean operator AND represents the interaction and convergence of two research fields and path-breaking technologies given by Quantum Technologies and AI.

Scientific products and patents are the basic units of documents and recorded knowledge for scientific and technology analyses that can clarify the evolution of science and technology here (cf., Glänzel and Thijs, 2012; Jaffe and Trajtenberg, 2002; Jiang and Shin-Liang Chen, 2021). Data do not consider 2023 because it is ongoing, and it does not affect the analysis of scientific and technological trends.

2.2 Measures of Variables

The scientific development is investigated considering:

Number of articles and all scientific products using keywords or combination of keywords with Boolean operators as indicted above.

For technology analysis, this study analyzes patents that indicate inventions and show the potential evolution of innovations (Jaffe and Trajtenberg, 2002):

Number of patents using keywords or combination of keywords with Boolean operators as indicted for the related period.

2.3 Technometric Modelling and Data Analysis Procedure

Working hypothesis is that interaction of scientific fields and radical technologies increases the co-evolutionary patterns of growth and supports scientific and technological change.

For a comparative analysis, data are standardized to represent the temporal evolution, focusing the period from 2000 to clearly show science and technological dynamics.

Trends of research field/technology i at t are analyzed with the following model:

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

y_t is scientific products or patents

t =time

u_t = error term

(a = constant; b =coefficient of regression; log has base $e=2.7182818$)

Secondly, science dynamics of research fields and technologies are also analyzed with a model based on spatial aspects of science evolution in which the number of patents (Y) is a function of the number of scientific production (X) over time. This model measures how the production of publications supports patents' growth and explains the relative rate of combined scientific-technological evolution (cf., Sahal, 1981). The structure of the model is as follows:

Let $Y(t)$ be the extent of advances of technology (e.g., in quantum technology) at the time t , measured with patents, and $X(t)$ be the scientific production underlying the advances of technology Y . Suppose that both X and Y evolve according to a S-shaped pattern that can be represented with a differential equation of logistic function. The logistic model has a symmetrical S-shaped curve with a point of inflection at $0.5K$; $a_{1,2}$ are constants that depend on the initial conditions (1 =Publications, 2 =Patents), $K_{1,2}$ are equilibrium levels of growth, and $b_{1,2}$ are rate-of-growth parameters. After some mathematical transformations (cf., Sahal, 1981), the differential equation of logistic function is a simple linear relationship (log-log model):

$$\log Y = \log A + B \log X \quad (2)$$

A =constant; B = evolutionary coefficient of growth that measures the evolution of Y (patents, response variable) in relation to scientific production X (drivers or explanatory variable).

The coefficient of relative growth B in the model (2) indicates different pathways of evolution:

$B < 1$, whether Y (patents evolves at a lower relative rate of change than X (scientific production); the whole scientific-technological system has a slowing down evolution over the course of time.

$B = 1$, then Y and X (patents and publications) have a proportional evolution over time: (pathway of proportional growth).

$B > 1$, whether Y evolves at greater relative rate of change than X ; scientific-technological system has an accelerated evolution of patents Y compared to publications X over the course of time.

The estimation of model (2) is with Ordinary Least Squares (OLS) method that determines the unknown parameters in regression models. Statistical analyses are performed with the IBM SPSS Statistics 26®.

3. Results

Firstly, data are transformed in logarithmic scale to have normality in the distribution of variables for appropriate parametric analyses and robust results.

Table 3, using the coefficients of regression in estimated relationships of models (1), represented in Tables 1 and 2 (trends are displayed in Figures 1 and 2), reveals that the interaction of Quantum technology and Artificial Intelligence generates a high rate of growth in particular when patents are considered.

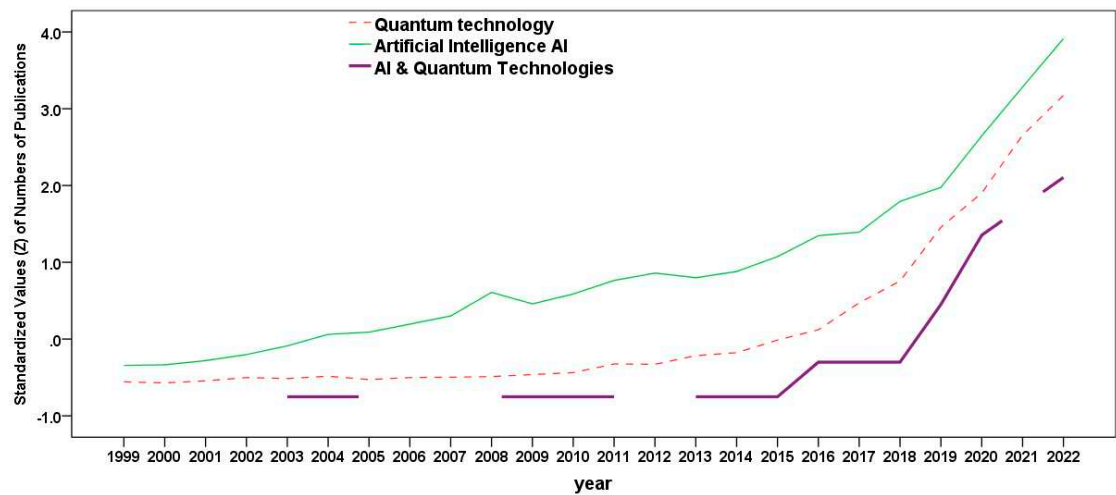


Figure 1. Trends of research fields using data of scientific production (standardized Z for comparative analysis). *Note:* to show better the trends, the period starts from 2000.

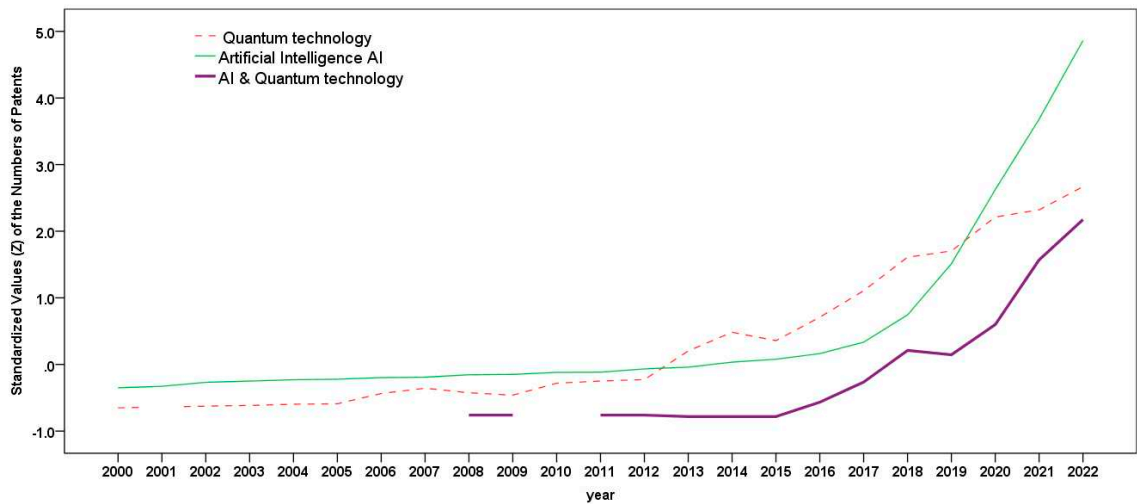


Figure 2. Technological trajectories using data of patents (standardized Z for comparative analysis). *Note:* to show better the trends, the period starts from 2000.

Table 1. Estimated relationships of scientific production (publications) as a function of time.

| Dependent variable: scientific products concerning scientific fields and technologies | | | | |
|---|------------|------------|-----------|----------------|
| | Coefficien | Constant | F | R ² |
| | t b1 | a | | |
| Quantum technology, Log y pubs i,t | .206*** | −410.73*** | 370.47*** | .93 |
| Artificial Intelligence, Log y pubs i,t | .155*** | −301.58*** | 720.43*** | .92 |
| Artificial Intelligence and Quantum Technology, Log y pubs i,t | .172** | −345.00** | 14.89** | .61 |

Note: Explanatory variable is time in years. *** significant at 1%; ** significant at 1%. F is the ratio of the variance explained by the model to the unexplained variance. R² is the coefficient of determination.

Table 2. Estimated relationships of patents as a function of time.

| Dependent variable: Patents | | | | |
|---|-----------------------|---------------|-----------|----------------|
| | Coefficient b'_1 | Constant a' | F | R ² |
| Quantum technology, $\text{Log } y \text{ Patents}_{i,t}$ | .217*** | −432.61*** | 516.72*** | .94 |
| Artificial Intelligence, $\text{Log } y \text{ Patents}_{i,t}$ | .199*** | −391.87*** | 514.97*** | .91 |
| Artificial Intelligence and Quantum Technology, $\text{Log } y \text{ Patents}_{i,t}$ | .416** | −835.95** | 29.60** | .72 |

Note: Explanatory variable is time in years. *** significant at 1%; ** significant at 1%. F is the ratio of the variance explained by the model to the unexplained variance. R² is the coefficient of determination.

Table 3. Evolutionary growth of publications and patents based on coefficients of regression of Tables 1 and 2.

| | Coefficient of Publications | Coefficient of Patents |
|--|-----------------------------|------------------------|
| Quantum Technology | 0.206 | 0.217 |
| Artificial Intelligence | 0.155 | 0.199 |
| Quantum technology and Artificial Intelligence | 0.172 | 0.416 |

The evolution driven by science and technology advances is in Table 4. Results, based on equation (2), show $B>1$ (a disproportionate and accelerated growth of patents compared to publications over time) suggesting an accumulation of inventions to support innovations for next industrial and social change driven by knowledge production in quantum science and technology (Table 4).

Table 4. Parametric estimates of the model of scientific-technological evolution.

| Estimated relationship | | | |
|--|----------|-----------------|-----------------|
| Quantum technology | log Y= | .257 | +1.067logX |
| | | (0.244) | (0.06) |
| | | ns | <i>p</i> <0.001 |
| | | R²=0.914 | S=0.683 |
| Artificial Intelligence | log Y''= | −5.016 | +1.375logX' |
| | | (0.477) | (0.060) |
| | | <i>p</i> <0.001 | <i>p</i> <0.001 |
| | | R²=0.910 | S=1.015 |
| Quantum technology and Artificial intelligence | log Y''= | 0.407 | +1.583logX'' |
| | | (0.412) | (0.225) |
| | | <i>ns</i> | <i>p</i> <0.001 |
| | | R²=0.874 | S=0.664 |

Note: Y = Patents; X= Publications; The standard errors of the regression coefficients are given in parentheses. p is the p-value. R² 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. ns=not significant; *** significant at 1%.

4. Discussions Considering Previous Research

Using temporal and spatial models of evolution, based on data of publications and patents, statistical analyses reveal that the interaction of these path-breaking research fields and technologies (Quantum technology and Artificial intelligence) have an accelerated rate of patents given by 0.42 compared to single technologies individually (Artificial Intelligence with 0.20 and Quantum technology with 0.22). Moreover, the model of spatial evolution (Sahal, 1981) in which patents are driven by publications shows that interaction of Quantum technology and Artificial intelligence has a relative growth of 1.58, higher than quantum technology with 1.07 and Artificial Intelligence 1.37, individually. This result suggests that interaction of path-breaking research fields and emerging technologies is basic to accelerate co-evolution for laying the foundations for scientific and technological in science, technology and society. Scholars have showed that interaction among technologies can support technological evolution, and this result here is consistent with one of the multi-modes interaction of Utterback et al. (2019) given by symbiosis where each of the technologies enhances the other's growth rate. A multi-mode framework of technological interaction can provide a setting within which to better analyze and understand the dynamics of technological change between two or more technologies. The interaction between scientific fields and technologies creates the opportunity for scientific cross-fertilization and more strategic possibilities that are not possible with a single technology. In the case under study, the interaction generates high growth rates and a symbiotic-dependent evolution between research fields and technologies. The concept of symbiosis is closely related to that of mutualism (it is any type of relationships in which each scientific fields or technology benefits from the activity of the other one; cf., Coccia, 2019) and to commensalism, which is any type of relationships between two research fields or technologies where one benefits from the other without affecting it (Coccia and Watts, 2020). With respect to the scientific and technological systems of interest here, results suggest a symbiosis that seems to be the more appropriate interaction, supporting growth rate of research fields and technologies. The confluence of these scientific fields and technologies generates a high potential for improving human lives in many ways (Burger et al., 2023; Dhamija and Bag, 2020).

In fact, rapid advances in convergent research fields and technologies have the potential to enhance both human performance and the nation's productivity (Roco and Bainbridge, 2002). Interaction of artificial intelligence and quantum technology can generate synergistic combinations and foster emerging technologies and major innovations, which are currently progressing at a rapid rate (Tables 3 and 4). Revolutionary advances at the interfaces between previously separate fields of science and technology are ready to create disruptive innovations, including instruments, analytical methodologies, and radically new systems. Progress of this interaction, just mentioned, can become self-catalyzing and can give the means to deal successfully with challenges in manifold fields and industries opening completely new opportunities (Burger et al., 2023; Cushing and Osti, 2023; Krinkin et al., 2023; Roco and Bainbridge, 2002; Zhao et al., 2021).

5. Conclusions

Results here suggest that artificial intelligence and quantum computing are growing with a high pace (cf., Arute et al., 2019; Coccia et al., 2022, 2024; Dowling and Milburn, 2003). Moreover, findings reveal that the interaction of these research fields and technologies has creating a symbiotic interaction with synergic effects on growth rate.

Theoretical characteristics of the interaction of recorded knowledge in research fields and technologies under study can be:

The long-run behavior and evolution of research field and technology is not independent of the behavior of other inter-related technologies.

Scientific and technological interaction between research fields and technologies generates a higher growth rate than each domain individually. This can be due to the symbiosis-dependent coevolution where each of research fields and technology enhances the other's growth rate.

The learning processes are a driving force of scientific and technological cross fertilization underlying the interaction between research fields and technologies.

The Innovation management implications from technological interaction is that financial resources on vital fields of research can be an accelerator factor of progress and diffusion of science and technology (Mosleh et al., 2022; Roshani et al., 2021). Policymakers and R&D managers can apply results of this study for an effective allocation of resources towards interacting and converging research fields and technologies to foster the development of new knowledge, scientific research and innovations for a positive impact in science and society.

However, the complexity of investigating evolutionary pathways in quantum technologies and artificial intelligence is due to different scientific and technological aspects. The conclusions of this study are, of course, tentative. Although this paper has provided some interesting, albeit preliminary results, it has some limitations.

First, natural sciences are well-represented in databases, but the literature of technical sciences can be only partly represented in the literature databases; the research output in engineering and computer sciences, in addition to publications and patents can be also software. In fact, sources under study may only capture certain aspects of the ongoing dynamics of quantum science and AI. Databases here are reliable but their coverage is limited especially in computer sciences, and they need to enlarge their scope to cover all forms of research outputs, also including software (Leydesdorff, 2008).

Second, the search queries generate wide sets that need in future a better cleaning and refinement to reduce overlap in data. A complementary approach to refine investigations can be methods of mapping to analyze the evolution of network structures in quantum technologies and artificial intelligence. For instance, maps of connections between key papers can clarify the pathways of main interactions driving scientific and technological evolution. This mapping can be associated with co-citation analyses that use multivariate techniques to identify and examine the networks of new scientific domains (Small, 1973; Coccia et al., 2022s). Therefore, the scientometric analysis of complex fields—e.g., quantum technologies and artificial intelligence— requires a combination of different approaches (e.g., field terminology for appropriate lexical queries, analysis of citation flows, structured interviews with scholars and R&D managers, etc.) to provide comprehensive results.

A third limitations is the presence of inter- or trans- disciplinary research that plays a vital role in the evolution of quantum technologies and artificial intelligence. To overcome this limit and improve the analysis of technological pathways, future studies should be integrated with the approaches by Leydesdorff and Rafols (2011) that have developed citation-based metrics to measure the interdisciplinarity of journals or by Silva et al. (2013). Fourth limit is due to multiple confounding factors (e.g., R&D investments, collaboration intensity, openness, intellectual property rights, etc.) that affect the dynamics of scientific fields and technologies under study and should be included in future studies to confirm growth rates in scientific and technological development.

Despite these limitations, the results presented here illustrate critical effect of interaction that generates higher growth rate to lay the foundation for the emergence of a radical scientific and technological change. These results can guide appropriate R&D investments of policymakers and R&D managers to foster higher interaction that creates the background for discoveries and innovations for increasing beneficial impact in science, market and society (Mosleh et al., 2022; Roshani et al., 2021). The results presented here clearly point out the need for more detailed scientific and technological analyses to clarify the drivers of the evolution of emerging scientific fields and technologies to support appropriate R&D management implications and research policies that accelerate. To conclude, if we want the great benefits of quantum technology and artificial intelligence interaction, policymakers should increase R&D investments to foster their convergence. As a result, the positive impact of these research fields and technologies on the current and future human development and quality of life will be higher with benefits in science and society.

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