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Abstract: Variability is the predisposition of phenomena to assume different values over time. Variability is higher when the differences of cases from each other are larger or diverge from a specific value, such as arithmetic mean. This study focuses on the variability of research topics within and between research fields to explain, whenever possible, how the variability shapes the structure and dynamics of technological trajectories. Analysis of variability here applies the entropy and variance decomposition on main research fields in quantum technologies. Empirical evidence shows that variability in research topics is inversely proportional to the age of research fields. Inductive implications are that higher variability in research topics of recent scientific fields is due to uncertain dynamics that generates a heterogeneity of different technological trajectories some of them can growth and develop towards fruitful directions others can be dismissed. Hence the variability seems to be one of the drivers that shapes technological evolution and can provide policy and managerial implications to improve the scientific and technological forecasting that may support appropriate decisions of R&D investments towards promising research fields and technologies.

Keywords: science of science; scientific development; research fields; quantum technology; quantum science; entropy; technological evolution; technological change

1. Introduction

Technological evolution has a basic role in scientific, economic and social development of human society (Arthur, 2009; Basalla, 1988; Bryan et al., 2007). The study here endeavors to examine the variability of research topics to explain the causes and different characteristics driving the scientific and technological evolution. Proposed theoretical framework here is developed with an evolutionary perspective of technological change guided by generalized or universal Darwinism (Dawkins, 1983; Nelson, 2006; Levit et al., 2011). Hodgson (2002, p. 260) maintains that: "Darwinism involves a general theory of all open, complex systems". In this context, Hodgson and Knudsen (2006) suggest a generalization of the Darwinian concepts of selection, variation and retention to explain how a complex system evolves (cf., Hodgson, 2002; Stoelhorst, 2008). In the economics of technical change, the generalization of Darwinian principles ("Generalized Darwinism") can assist in explaining the multidisciplinary nature of innovation processes (cf., Hodgson and Knudsen, 2006; Levit et al., 2011; Nelson, 2006; Schubert, 2014; Wagner and Rosen, 2014). In fact, the heuristic principles of "Generalized Darwinism" can explain aspects of technological development considering analogies between evolution in the biological sense and similar-looking processes in the evolution of technology (Farrell, 1993; Oppenheimer, 1955). Arthur (2009) argues that Darwinism can explain technology development as it has done for the development of species (cf., Schuster, 2016, p. 7). In general, technological evolution, as biological evolution, displays radiations, stasis, extinctions, and novelty (Kauffman and Macready, 1995; Solé et al., 2013). Kauffman and Macready (1995, p. 26) state that: "Technological evolution, like biological evolution, can be considered a search across a space of possibilities on complex, multipeaked 'fitness,' 'efficiency,' or 'cost' landscapes". Schuster (2016, p. 8) shows the similarity between technological and biological evolution, for instance technologies have

finite lifetimes like biological organisms. In this perspective, the principle of selection can explain the successful in evolution of some technologies (e.g., their survival and diffusion in markets). In particular, the concept of selection works if there are significant differences between the elements making up the population: i.e., it is necessary the variation (Bowler, 2005). Mutatis mutandis for technologies, using the theory of Darwin:

Natural selection is the process through which populations of living organisms adapt and change. Individuals in a population are naturally variable, meaning that they are all different in some ways. This variation means that some individuals have traits better suited to the environment than others. Individuals with adaptive traits—traits that give them some advantage—are more likely to survive and reproduce. ... Over time, these advantageous traits become more common in the population (Natural Geographic, 2023).

In short, variation, associated with selection, generates processes through which (human or technological) species adapt to environments and evolve over time. However, the role of variation in the domain of technologies is hardly known but it can be basic to explain important characteristics and sources of technological evolution. The general theoretical background of "Generalized Darwinism" (Hodgson and Knudsen, 2006), described here, can frame a broad analogy between technologies and evolutionary ecology that provides a logical structure of scientific inquiry to analyze variability in science driving different pathways of technologies and innovations in society (Coccia, 2019). The goal of this study is to clarify the concept of variation within and between technologies to examine the effects in evolutionary pathways. In fact, technology analysis of the variation in technological domains can create the framework within which a synthesis of basic properties on evolutionary pathways could be worked out, extending lines of research of evolutionary economics to clarify the science dynamics and technological evolution. Therefore, as the variation can be considered one of the engines that drives evolution of technologies, it deserves to be investigated because the understanding of the nature of variation in science can extend the theories of technological evolution with a new conceptual element that can explain the emergence, evolution and new directions of technological trajectories in turbulent (complex and uncertain) markets supporting social and economic change. The proposed theory of variability for scientific and technological evolution is verified empirically in main quantum technologies by applying entropy coefficient and other techniques that suggests empirical properties of technological evolution. Findings can support managerial and policy implications to improve technological forecasting and to direct R&D investments towards promising technologies and innovations for science and socioeconomic progress.

2. Research Methodology

2.1. Quantum Technologies

This study focuses on vital quantum technologies (quantum computing, quantum communication, quantum optics, etc.) that are basic technological systems having a high potential to improve information processing, communication, etc. (Coccia, 2022; Kozlowski and Wehner, 2019; Scheidsteger et al., 2021; Tolcheev, 2018). Many quantum technologies are at the initial and/or infancy stage of evolution, but they have continuous scientific and technological advances directed to generate promising innovations to solve problems and improve socioeconomic systems (Atik and Jeutner, 2021; Carberry et al., 2021; Gill et al., 2022; Coccia, 2022). In fact, new quantum technologies can support, with powerful algorithms, quantum machine learning (Pande and Mulay, 2020; Rao et al., 2020), drug discovery process (Batra et al., 2021), cryptographic tasks (Chen et al., 2015), information processing of big data (cf., Latifian, 2022), etc.

2.2. Measures, Sample and Sources of Data

This study uses number of occurrences concerning research topics in scientific documents of main quantum technologies given by: Quantum Imaging, Quantum Meteorology, Quantum Sensing

and Quantum Optics. Data are from Scopus (2023), downloaded on 24 April 2023. In particular, the study considers all available data in:

- Quantum Meteorology: 1,851 scientific documents, with 8,646 occurrences concerning the first 160 research topics having the higher frequency (all data available from 1972 to 2023).
- Quantum Sensing: 1,375 scientific documents, with 6,618 occurrences concerning research topics concerning the first 160 research topics having the higher frequency (data from 2000 to 2023).
- Quantum Optics: 54,332 scientific documents, with 236,887 occurrences concerning research topics concerning the first 160 research topics with the higher frequency (data from 1958 to 2023).
- Finally, Quantum Imaging: 673 scientific documents, with 3,407 occurrences concerning research topics with the first 160 research topics having the higher frequency (data from 1996 to 2023).

In particular, the study analyzes the number of occurrences concerning research topics (indicated as number of keywords) in scientific documents of just mentioned quantum technologies over time (Glänzel and Thijs, 2012; Al-Betar et al., 2023; Zhang et al., 2023). Another measure used is the period of time from first available scientific document to 2023 to associate technological analysis to the temporal dimension (*chronos*).

2.3. Methods for Statistical Analysis of Data

The analysis of variation of research topics in four homogeneous groups of quantum technologies above can clarify characteristics and dynamics of the technological evolution over time. The analysis of variation in technologies is based on following measures and statistical techniques.

Variance indicates a measure of dispersion that considers the spread of all data points in a dataset, research topics   in this study,

$$S^2 = \frac{\sum_i (x_i - \bar{x})^2}{n-1} \qquad (1)$$

$S^2 = Variance$
$x_i = value\ of\ one\ case\ (research\ topics\ in\ a\ year)$
$\bar{x} = average\ value\ of\ all\ cases\ (research\ topics\ of\ all\ years)$
$n = number\ of\ cases\ (years)$

The variance measures the (quadratic) spread around the mean (Girone and Salvemini, 1981).

Entropy is a measure of heterogeneity (Gini, 1912, Nunes et al., 2020, Rényi, 1961; Shannon, 1948, Simpson, 1949; Lin et al., 2021; cf., Takahashi et al., 2023). Given a population (here data on a specific quantum technology) in which the research topics have a relative frequency Pi , Shannon suggested the degree of indeterminacy in predicting the modality of a unit chosen at random from population on the basis of the entropy index. The entropy index is a decreasing function of the variability of the relative frequencies (Grupp, 1990; Jost, 2006, Lin et al., 2021; Zidek and van Eeden, 2003). In brief, H(X) is the entropy of a single distribution (X), given by:

Entropy $H(X) = -\sum_{i=1}^{s} P_i(x) \log P_i(x) \qquad (2)$
where Pi(x) =ni/N
s= distinct modes

H has a value of 0 when the whole frequency is concentrated in a single modality. H gradually increases values as the heterogeneity of the modalities increases up to the maximum of: Max H=log s when there are s distinct modes all with the same absolute frequency N/s. The relative entropy index is:

$$H = \frac{H(x)}{\log s} \qquad (3)$$

The correlation coefficient of Pearson between relative indices of entropy in quantum technologies and their scientific age starting from the first scientific document to 2023 (year of the current analysis) suggests the direction of the association. Moreover, simple regression analysis is applied to show a preliminary estimated relationship, using ordinary least squares method, based on inverse model given by:

y=α+β(1/x) $\qquad (4)$

The study also applies the variance decomposition analysis (cf., Gibbons et al., 2014) to analyze the total variance (and therefore the variability) in relation to that of the more homogeneous subgroups (four classes of quantum technologies here). This approach can clarify the search of factors that affect the inequality in statistical units considering the contribution to total deviance (note that deviance is the numerator of variance in eq. 1 above). Finally, in order to verify whether the entity of the deviance between groups is significantly greater than the deviance obtained as a result of the sample fluctuations, it can be compared with the deviance within groups . This statistical analysis is done with the ANOVA ("Analysis Of Variance") F-test.

3. Results

Table 1 shows that quantum optics has a higher concentration of occurrences in research topics (lower relative entropy), whereas Quantum sensing has higher heterogeneity of these occurrences in manifold research topics (higher relative entropy). This result can be due to the scientific age of quantum sensing that is shorter (23 years) than quantum optics that has an evolutionary period of 65 years. Moreover, higher heterogeneity suggests that younger research field has to stabilize the technological trajectories and directions in evolutionary patterns (Dosi, 1988, 1988a).

Table 1. Relative entropy between quantum technologies, and related scientific age.

	N	Arithmetic Mean	Std. Deviation	Relative H	Year of the First Scientific Product	Scientific Age in 2023
Quantum Optics	154	1480.48	4235.48	0.827	1958	65
Quantum Metrology	154	54.04	113.00	0.853	1972	51
Quantum Imaging	152	21.29	42.10	0.866	1996	27
Quantum Sensing	153	41.36	46.59	0.925	2000	23

Table 2 shows r=−0.951 (p-value 0.05): a negative association between relative entropy and scientific age in classes of quantum technologies under study: i.e., younger technologies have a higher entropy index, suggesting a higher heterogeneity of the frequency of occurrences between manifold research topics.

Table 2. Bivariate Correlation between relative entropy and scientific age in quantum technologies.

		Relative Entropy, H	Scientific Age of Quantum Technology
Pearson Correlation, r	Relative Entropy, H	1	−0.951*
Sig. (2-tailed)			0.049
N		4	4

* Correlation is significant at the 0.05 level (2-tailed).

Table 3 shows analysis of regression of a preliminary estimated relationship with inverse model concerning entropy on scientific age. Although R^2 is very high, showing a high goodness of fit of the inverse model, coefficient of regression β is not significant because of limited sample. Hence, this analysis provides an approximation of the possible inverse relationship between scientific age of technology and relative entropy that measures indeterminacy and variability of research topics within technologies that are driving evolutionary patterns.

Table 3. Parametric estimates of the relationship with inverse model.

Explanatory Variable: 1/ Scientific Age of Quantum Technology				
Dependent variable	Constant	Coefficient	R^2	*F*

	α	β		
Relative Entropy H	78.90***	272.73	.80	7.95

Note: *** $p<0.001$.

Table 4 shows the deviance decomposition between groups of quantum technologies under study. Results suggest that 91.74% of statistical deviance is within groups, whereas 8.26% is between groups. Although the deviance within groups clearly prevails, the deviance between the groups assumes a non-negligible value. Deviance between groups can be the consequence of the diversity of averages and stand. deviation between the groups of quantum technologies under study, associated with different scientific ages, which lead some technologies to have more occurrences and others (more recently originated fields) to have less ones. Finally, the One-Way ANOVA between groups of quantum technologies shows a high value of F-test that leads to a significance level of 0.001. Therefore, the analysis of the deviance decomposition and ANOVA suggest that the between-group variability is unlikely to be due to circumstances related to the data collection. This result suggests a systematic effect of the nature of specific fields in quantum technology that generates a greater or lesser heterogeneity and diversity of the frequency of occurrences in different research topics during the evolutionary paths of the technologies themselves. *Hence, sources of the variability between research fields can be the specific nature of research fields, their scientific age and magnitude (amount) of scientific production over time.*

Table 4. Deviance decomposition in groups of quantum technologies in percent value and ANOVA.

Nature of variability (Deviance)	%	Degrees of Freedom	F-test	p-Value (Significance)
BETWEEN GROUPS	8.26	3		
WITHIN GROUPS	91.74	609	18.29	0.001
TOTAL	100	612		

4. Scientific Explanation and Scientific Implications

The study of the variability within scientific and technological pathways can show main characteristics and properties of the dynamics of evolution. Higher variability indicates higher dispersion of values in evolutionary patterns, and in the case of quantum technologies, high variability, measured with relative entropy, reveals that statistical units (occurrences of research topics in scientific documents) of these technologies have a low homogeneity between research topics. This study of the variability is the basis of the scientific investigation of the causes underlying higher or lower dispersion in relation to the nature of the research fields driving technological evolution. The different variability of the observed occurrences in research topics can be used to characterize the specificity of technologies and their evolutionary patterns. Moreover, higher variability, such as in the case of quantum sensing, also indicates a limited possibility of generating reliable technological forecasting, unlike quantum optics that is a more mature research field. In short, results suggest that a high variability in some technologies is a sign of various underlying causes (of random or systematic nature) that affect in different ways the evolutionary patterns. The method of investigation here, based on generalized Darwinism, can suggest basic driving forces of scientific variability driving technologies given by:

- The specificity of the technologies. If the technological nature is more oriented to be a general purpose technology for other inter-related technologies, such as quantum sensing rather than quantum optics, the endogenous variability within the complex system of technology can be higher, suggesting the indeterminacy in evolutionary trajectories and related technological forecasting (Coccia, 2020).

- Scientific age of the scientific production: a shorter age induces a higher variability than technologies having a longer scientific age.

- The accumulation of scientific knowledge (papers) is also a factor determining variability because a lower accumulation of scientific products in younger research fields induces a higher variability and uncertainty in technological trajectories, whereas a higher accumulation of scientific outputs is associated with lower variability in mature (older) technologies.

These results show that the variation can be due to manifold sources. A mechanism determining the variation in just mentioned factors is the change of scientific and technological ecosystem in which scientific research and technologies develop. Moreover, internal mechanisms of variation in technologies can be associated with external mechanisms of variation, such as interaction of different research topics associated with technologies during evolutionary pathways (cf., Ke, 2023). Variability of technologies and in this case of quantum technology has a primary source in the behaviour of technologies that cannot survive and develop as independent systems *per se*, but they can function and evolve in environments in which interact with other inter-related technologies (Coccia and Watts, 2020). Coccia (2018) systematizes this general behaviour of technologies and sources of technological variability with the *theorem of not independence of any technology (Coccia, 2018)*: the long-run behavior and evolution of any technological innovation Ti is not independent from the behavior and evolution of the other technological innovations Tj, $\forall i = 1, ..., n$　and　$j = 1, ..., m$

Hence, technological interaction in the technological development can be a main source of spatial and temporal variability associated with different relationships between technologies given by (Coccia, 2019): technological parasitism, technological commensalism, technological mutualism and technological symbiosis. In fact, interaction between technologies generates a source of variability leading to coevolution of interrelated technological systems (cf., May, 1981). Hence, some technological variations depend more on the nature of the technology than on the nature of the conditions of ecosystem, but general changes in the conditions of ecosystem trigger scientific and technological variation. This result has a *complementary implication*: if it were possible to expose all technologies over time to absolute uniform environmental conditions, *without* interaction, there would be no variability. Or conversely, if there is variability, technology has to be necessarily exposed to changes in the conditions of ecosystem and interactions between technologies (cf., Coccia and Watts, 2020; Winther, 2000). In addition, changes in the stage of development are necessary conditions to induce variation: in the initial stage of development, variation tends to be high (e.g., in quantum sensing) with manifold potential emerging trajectories; in a stage of advanced development, when technology has a more stable evolutionary structure, variability tends to be lower (e.g., quantum optics). Finally, as mentioned before, with uniform conditions of development and without interactions between technologies, there is no variation and consequential coevolutionary patterns of growth (Coccia, 2019; Tolcheev, 2018; Jang et al., 2022; Winther, 2000).

In general, results here, with the analysis of the variance decomposition, show that variation is due to systematic characteristics of the nature of technology and unsystematic characteristics in innovation ecosystem, such as changes and random technological interaction with other technologies. In brief, the causes of variation in technologies that generate main evolutionary shifts can be: changes in the conditions of ecosystem; the nature of the technology can be more important than the nature of the changed ecosystem in determining the nature of the variation and co-evolution, and finally a larger proportion of variation in technologies is systematic and adaptive in changing socioeconomic systems (Coccia and Watts, 2020).

4.1. Principal Theoretical Implications

These results suggest some properties of variation in science that can contribute to explain the evolution of technologies and support technological forecasting for guiding R&D investments and management of technology for industrial and economic change:

Property 1. the growth of variability in research topics driving the evolution of technologies is inversely proportional to the age of research fields: younger technologies have a higher variability between research topics, whereas older technologies have a lower heterogeneity and more concentration of values in vital research topics suggesting stable evolutionary patterns. The inverse relation can be expressed with the following equation y=α + β (1/x). By using the four technologies

under study and empirical value of relative entropy % and scientific age of four research fields in years presented in table 3, the estimated model is (*law of variability in science guiding technological evolution*):

$$Entropy\ (H\%) = \alpha + \beta \left(\frac{1}{x}\right)\ = 78.90 + 272.73 \left(\frac{1}{age\ of\ scientific\ field}\right)^{.08}\ \ R^2 = 0.80$$

Property 2. The nature of research fields has systematic effects in driving technological variability and evolution of technology.

Property 3. Technological life cycles produce similar life cycles unless there are changes in ecosystem leading to technological interaction with other technologies, which generates variability and co-evolutionary patterns.

Property 4. Variation in technologies is due to changes in their related ecosystem, interactions between technologies and transformation of socioeconomic system.

Property 5. The accumulation of scientific knowledge is a factor affecting variability in scientific fields driving technologies: low accumulation of scientific products in emerging technologies induces a higher variability and indeterminate evolutionary pathways of technological trajectories, whereas a higher accumulation of scientific outputs in older research field is associated with a lower variability and more stable evolution of main technological trajectories.

5. Conclusions and Limitations

This study shows for the first time, to my knowledge, an analysis of variation within scientific domains to explain some properties of evolutionary pathways in technologies.. The broad analogy between evolutionary ecology and technological evolution, within a Generalized Darwinism, applied here keeps its validity in explaining the variability within and between research topics to clarify some aspects of technological evolution. However, the idea presented in the study here is adequate in some cases but less in others because of the diversity of technologies, their intrinsic nature and propensity of interaction in different complex systems and socioeconomic environments. These findings here can encourage further theoretical exploration in the terra incognita of the variability in scientific fields to clarify basic properties of technological evolution. The case study of quantum technologies shows different magnitude of variability driven by changes in endogenous dynamics and structure of innovation ecosystem over time (Coccia and Watts, 2020; Sun et al., 2013). Evidence suggests that a lower variability is associated with technologies having a longer scientific age, whereas technologies with a shorter scientific age, they have a higher variability that suggests a not clear direction of technological trajectories. Policymakers and R&D managers can use the findings here for making efficient decisions regarding R&D investments of specific technological trajectories (Coccia, 2022; Roshani et al., 2021; Mosleh et al., 2022).

These conclusions are, of course, tentative. This study provides some interesting but preliminary results in these complex fields of research related to the evolution of emerging technologies. Some limitations are that: 1) scientific outputs and research topics can only detect certain aspects of the ongoing dynamics of quantum research and technology and next study should apply complementary analysis based on patents for improving results and managerial implication also for technological foresight; 2) confounding factors (e.g., level of public and private R&D investments, international collaboration in specific quantum technologies, etc.) affect the evolution of quantum technologies and these aspects have to be considered in future studies to improve data gathering for new technological analyses; 3) An aspect to further investigate is the constraints on variation that technologies have during the adoption; finally, 4) model and estimated relationship between variability and scientific age have to be improved with more data to have robust statistical analyses. In short, there is need for much more detailed research into the investigation of the role of variability to clarify evolutionary patterns of technologies and support implications for innovation management and technological forecasting.

Despite these limitations, the study here clearly illustrates that a different variability can clarify basic characteristics of the technological change. To conclude, the proposed theoretical framework here based on analogy of scientific and technological evolution with some evolutionary aspects

present in ecology and biology may lay the foundation for development of more sophisticated concepts and theoretical frameworks in economics of technical change to explain and forecast science dynamics and technological evolution.

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