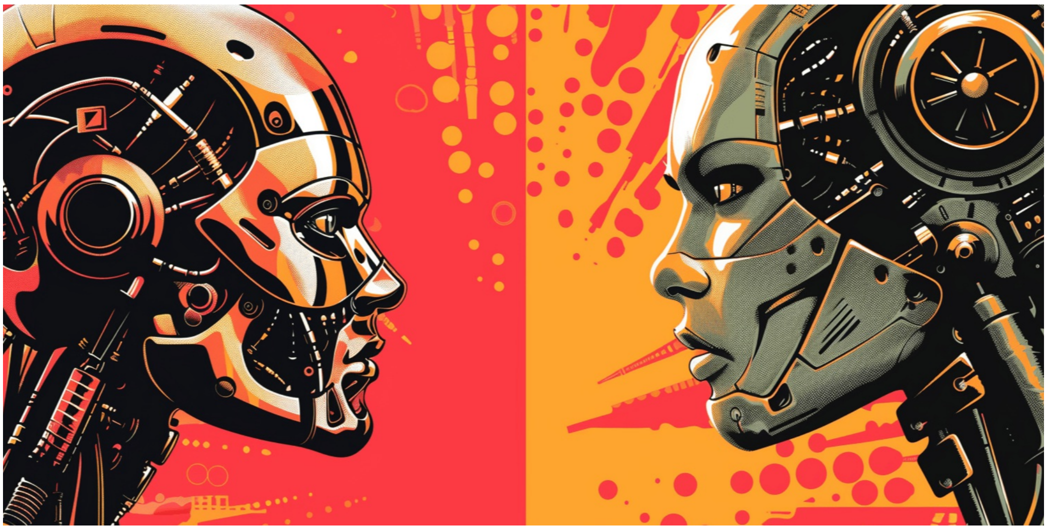

Foundations of Science in Invasive Technologies

Mario Coccia[1]

1 Italian National Research Council

Funding: No specific funding was received for this work.

Potential competing interests: No potential competing interests to declare.

Abstract

This study proposes that one of the drivers of technological change is the technological invasion of path-breaking technologies and innovations. Invasion is anything that breaks into a place, occupying it or spreading in large quantities. This aspect is present in botany with invasive plants, in biology with invasive organisms, or in medicine with invasive cancer cells. The extension of this concept to the field of technology can clarify the main dynamics of technological change. From a perspective of generalized Darwinism, the theory here suggests the invasive behaviour of technologies that expand the space of adjacent possible by introducing novelties and radical innovations with dynamic interaction between the actual and possible. The prediction of the theory, given by the acceleration rates of invasive technologies that conquer the space of alternative technologies, is tested in the emerging path-breaking technology of transformers (a type of deep learning architecture used in natural language processing – NLP – and in generative artificial intelligence). Transformer technology, introduced in 2017, has been developing radical innovations in pretrained language models (Generative Pretraining Transformers, GPTs) since 2018, such as OpenAI's GPT series, and Google's Bidirectional Encoder Representations from Transformers (BERT) model. Notable products include ChatGPT, introduced in November 2022, and Microsoft Copilot, which started in February 2023. Transformer technology and related radical innovations are spreading rapidly, invading and displacing other established technologies, changing the space of possibilities in human society. One significant way to understand the invasive behaviour of technologies is to estimate and analyze rates of spread. Statistical evidence here, based on patent analyses, reveals that the growth rate of transformer technology is 55.82% (over 2016-2023), more than double compared to 23.02% of all other technologies. The last three years (2021-2023) show that the growth rate is 25.81% for transformer models with an invasive and disruptive force on other technologies, having a mere 0.76% growth. Results are confirmed with a model of technological evolution that reveals a growth rate of invasive technology of transformers of 0.30 versus 0.13 for other technologies. Comparative analysis with a previous technology in neural networks, Convolutional Neural Networks (CNN), suggests that transformer architecture has a higher disruptive force that spreads rapidly, invading the space of other technologies (technological invasion) with radical innovations, generating a drastic technological shift and change in the space of possibilities. This accelerated dynamics of transformer technology driving generative AI that mimics human ability is due to leading firms (such as OpenAI with ChatGPT, Microsoft with Copilot, Google with BERT, Apple with its forthcoming GPT, etc.) that are creating the innovation ecosystem based on new platforms and products directed to applications and diffusion in markets for a main technological and industrial change. Overall, the invasive behaviour of transformer technologies and related innovations is fueling continuous innovations in the space of adjacent possible in generative AI and explains, in the current world of knowledge-based competition, the 'creative destruction' that has revolutionized the field of NLP with new products that invade current and new markets. Implications for the management of technology and innovation policy are suggested to support invasive technologies.

Mario Coccia

Research Director

CNR -- National Research Council of Italy

Department of Social Sciences and Humanities

IRCRES-CNR, Turin Research Area, Strada delle Cacce, 73-10135 - Turin (Italy)

E-mail: mario.coccia@cnr.it

Keywords: Transformer; Deep Learning Architecture; Generative Pretraining Transformers; GPTs; Large Language Models; Generative AI; Natural Language Processing; Emerging Technology; Radical Innovation; Invasive Technologies; Invasiveness; Adjacent Possible; Space of Possibilities; Technological Change; Technological Paradigm; Transformers; Attention Mechanism.

JEL Codes: O10; O31; O32; O33; O36; O39.

1. Introduction and Goal of Scientific Investigation

One of the fundamental problems in technological studies is how a drastic technology emerges, spreads, and sustains radical innovations for technological and social change (Dosi, 1988; Rogers, 1962; Sahal, 1981; Utterback et al., 2019;

Utterback, 1994). This study proposes that one of the drivers of technological change is due to the technological invasion of path-breaking technologies and innovations. Invasion is anything that breaks into a place, occupying it or spreading in large quantities. This aspect is present in botany with invasive plants that invade human habitats (Walker and Smith, 1997; Gholizadeh et al., 2024), in biology with invasive organisms when they are not indigenous to a particular area and can cause great economic and environmental harm to the new area (Pelicice et al., 2023), or in medicine with invasive cancer cells that have broken out of the lobule where they began and have the potential to spread to the lymph nodes and other areas of the body (de Visser and Joyce, 2023; Krakhmal et al., 2015). This study extends this scientific concept to consider the diffusion of technologies. This suggested interpretation of a basic determinant of technological change is tested by analyzing the new technology of the transformer model (a neural network) to explain the invasive behaviour underlying the scientific and technological change in generative Artificial Intelligence (AI). The invasive behaviour of new technology is especially relevant in a world of knowledge-based competition to clarify the 'creative destruction' in existing competences and products with pervasive diffusion in science, markets, and society having rapid changes (Teece et al., 1997; Tripsas, 1997). The proposed theoretical framework of invasive technologies can clarify the main characteristics of ongoing technological change for supporting R&D management and innovation policy in emerging technologies having a high potential impact in almost every sphere of human activity in the current information and digital era (Hicks and Isett, 2020). The understanding of the technological invasion of radical technologies is basic for understanding the evolution of new technologies, the emergence of major innovations, and the design of best practices for allocating resources to support emerging technological trajectories with unparalleled potential for growth to influence industrial and economic change (Roco and Bainbridge, 2002). The background of this study is the increasing availability of documents, patents, and recorded knowledge that offers main opportunities for theoretical and empirical explorations about new aspects in the emergence and evolution of radical technologies (Arthur, 2009; Fortunato et al., 2018; Iacopini et al., 2018; Nelson, 2008) that pave the way for the development of many inter-related technologies by "expanding the adjacent possible" (Coccia, 2018; Coccia and Watts, 2020; Kauffman, 2000, 2016, 2019; Kauffman and Clayton, 2006; Kauffman and Gare, 2015; Lehman and Kauffman, 2021; Wagner and Rosen, 2014). The proposed interpretation of invading technologies can explain important aspects of technological evolution and economic change in modern societies increasingly based on the high speed of knowledge and information turnover. One significant way to understand the invasive behaviour of technologies is to estimate the rates of spread in technological space having different and alternative technologies. Overall, then, the proposed theoretical framework of invasive technologies can clarify the main aspects of disruptive technologies to explain modern scientific and technological change for a better theory to support effective science and technology policy implications for societal benefits.

2. Critique and Limitations of Current Theories in the Evolution of New Technology

Some studies suggest the notion of technological paradigms and trajectories to explain the determinants and directions of technical change based on the solution of specific technological problems that also generate normal problem-solving activity in the domain of the technological paradigm (Dosi, 1988; Foster, 1986; Freeman, 1974; Nelson, 2008; Rosenberg, 1976). Other studies in technological dynamics have attributed the emergence and evolution of technologies to new discoveries (Basalla, 1988; Coccia, 2022; Tria et al., 2018). Different approaches focus on university-industry-government relations (Etzkowitz and Leydesdorff, 1998), converging systems of preexisting technologies (Barton, 2014; Roco and Bainbridge, 2002; Farrell, 1993), and problem-driven approaches in the emergence of radical technologies (Coccia, 2016, 2017, 2017a). The birth and evolution of radical technologies are also explained by social interactions among scientists and scientific communities (Crane, 1972; Sun et al., 2013; Wagner, 2008) and the leading role of some firms in markets (Coccia, 2018; Denning, 2018; Den Hartigh et al., 2016). Although there is vast literature, quantitative works on the invasive behaviour of path-breaking technologies in domains with manifold alternative technologies are lacking to date, owing in part to the difficulty of formally analyzing overall aspects of the pervasive diffusion and evolution of new technologies, based also on intangible aspects (e.g., software, algorithms), that generate technological shifts, industrial and technological impact in the current knowledge and information economy. Regardless of the sources of radical technologies, technology analysis of the specific dynamics of pervasive diffusion that generate radical changes in a short period of time is critical to scientific and technological development and the progress of human society (Bettencourt et al., 2009). The goal of this study is to propose in science the invasive behaviour of technologies to analyze the dynamics of path-breaking technologies that destroy established technologies, occupy their space, and become the dominant technology supporting technological and social change. The proposed theory is tested with a patent analysis of emerging path-breaking transformer technology (a type of deep learning model used in natural language processing – NLP – and in generative Artificial Intelligence). The transformer architecture was introduced in 2017, and from 2018 it has been developing pretrained language models (Generative Pretraining Transformers, GPTs), such as OpenAI’s GPT series and Google’s Bidirectional Encoder Representations from Transformers (BERT) model, with radical innovations of ChatGPT introduced in 2022 and Microsoft Copilot started in February 2023. The proposed theoretical framework of invasive technologies and analysis of findings can suggest the main characteristics of modern technological change and support theoretical and policy implications for the management of new technologies directed to support economic and social change.

3. Theoretical Framework and Research Setting

Path-breaking technologies have the characteristic of destructive behaviour that generates radical innovations based on new products and/or processes, which have high technical and/or economic performance directed to reduce market share or destroy the usage value of established technologies/products/processes previously used in markets (Christensen, 1997; Christensen et al., 2015; Tria et al., 2014). Calvano (2007) maintains that “Destructive Creation” is the deliberate introduction of new and improved generations of products that destroy, directly or indirectly, current products, inducing consumers to change their habits with consequential economic and social change. The dynamics of disruptive technologies generate technological, industrial, economic, and social change (Coccia, 2020). Adner (2002, pp. 668-669) claims that: “Disruptive technologies... introduce a different performance package from mainstream technologies” (cf., Adner and Zemsky, 2005; Calvano, 2007; Coccia, 2019). Abernathy and Clark (1985, pp. 4ff. and pp. 12-13, original emphasis) claim that:

> *An innovation is... derived from advances in science, and its introduction makes existing knowledge in that application obsolete. It creates new markets, supports freshly articulated user needs in the new functions it offers, and in practice demands new channels of distribution and aftermarket support. In its wake it leaves obsolete firms, practices, and factors of production, while creating a new industry... innovation that disrupts and renders established technical and production competence obsolete, yet is applied to existing markets and customers, is... labelled 'Revolutionary'. It thus seems clear that the power of an innovation to unleash Schumpeter's 'creative destruction' must be gauged by the extent to which it alters the parameters of competition, as well as by the shifts it causes in required technical competence. An innovation of the most unique and unduplicative sort will only have great significance for competition and the evolution of industry when effectively linked to market needs.*

Christensen (1997) argues that disruptive technology has specific characteristics: a) higher technological performance; b) products/processes that satisfy needs demanded by the mainstream market. Christensen et al. (2015) claim that disruptive technologies can be generated by small firms with fewer resources that successfully challenge established incumbent businesses (e.g., the case of OpenAI for ChatGPT, founded in 2015). Innovative firms, generating disruptive technologies and innovations, grow more rapidly than others (Abernathy and Clark, 1985; Tushman and Anderson, 1986, p. 439). Christensen's (1997) approach also shows that disruptive technologies or innovations (these terms are used here interchangeably) generate significant shifts in markets and society (cf. Henderson, 2006). In general, technological and market shifts of path-breaking technologies embody competence-destroying and competence-enhancing because these technologies can either destroy or enhance the competence of established technologies existing in industries (cf. Hill and Rothaermel, 2003; Tushman and Anderson, 1986). Moreover, disruptive innovations undermine the competences and complementary assets of existing producers and change the habits of consumers, fostering economic changes in many sectors (Christensen and Raynor, 2003; Garud et al., 2015; Markides, 2006; cf. Coccia, 2005). The diffusion and growth rate of disruptive innovation are also important drivers to create and sustain the competitive advantage of firms and nations amidst rapidly changing business environments (Kessler and Chakrabarti, 1996, p. 1143; Porter, 1980). Disruptive technology also affects the behaviour of other technologies, generating a process of actual substitution of a new technique for the established one and, as a consequence, convergence of manifold technologies generating new technological paradigms and trajectories for technical, industrial, and corporate change (Sahal, 1981; Fisher and Pry, 1971).

The proposed development of an invasive technology approach is basic to explain the evolution of technologies in modern knowledge-based economies having rapid change. A significant goal here is to understand the invasive behaviour of technologies by analyzing the rates of spread. The next section presents the research philosophy, methodology, and study design to structure the theory and test the prediction with empirical evidence.

4. Conceptual Framework

4.1. Research Philosophy

The 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, and in the Science of Science (Sun et al., 2013), the generalization of Darwinian principles ("Generalized Darwinism") can assist in explaining the multidisciplinary nature of scientific and technological 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 scientific and technological development, considering analogies between evolution in biological systems and similar-looking processes in science and technology (Oppenheimer, 1955; Price, 1986). Arthur (2009) argues that Darwinism can explain technology and science development as it has been done for the development of species in the environment (cf., Schuster, 2016, p. 7). In general, technological and scientific evolution, like 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. From this perspective, the principle of selection can explain the success in the evolution of some research fields and technologies (e.g., their survival and diffusion in markets, Bowler and Benton, 2005). However, the invasive behaviour in the domain of science and technology is hardly investigated in social studies of technology, but it can be basic to explain important characteristics of technological evolution. The general theoretical background of "Generalized Darwinism" (Hodgson and Knudsen, 2006), described here, can frame a broad analogy between science and technology and evolutionary ecology that provides a logical structure of scientific inquiry to analyze the invasive behaviour of technologies in economic systems and society (Coccia, 2019; Ziman, 2000). In fact, the goal of this study is to propose the approach of technological invasion to clarify dynamics in scientific and technological evolution that guide the diffusion of technologies in scientific and technological domains having alternative or competitive technologies. In fact, technology analysis of technological invasion can create the framework within which a synthesis of basic properties on evolutionary pathways could be worked out, extending lines of research in economics to explain technological evolution. Therefore, since the invasion dynamics is assumed to be one of the characteristics that clarifies the evolution of technology, it deserves to be investigated because the understanding of the role of invasive technologies can extend the theories of technological evolution with a new conceptual approach.

4.2. Theory of Invasive Technologies

Invasive organisms or elements play important roles in both the economy and ecology (Wang and Kot, 2001). However, the role of invasive behaviour in the study of technologies and innovations is not well known, but its examination is fundamental for uncovering new aspects of technological evolution. In a broad analogy with principles of biological systems, the recognition that invasive technologies are central to explaining evolutionary processes is crucial for determining the main properties of technological evolution.

Some basic concepts structure the proposed theoretical framework:

- Invasion is an organism or element that bursts into a space, occupying it or spreading in large quantities.
- Invasive technologies can replace, in a specific space, other technologies over several life cycles, producing new technologies and innovations that have the potential to spread in different domains and sectors, leading to technological, economic, and social change in the invaded environment ('impacts').

Postulates

- Invasive technologies are fundamental for technological change.
- Invasive behaviour ⇒ technological evolution.
- Invasive technologies, as new technologies, change the environment and have profitable adaptive behaviour to changing environments and, at the same time, eliminate the less suitable technologies, leaving the more suitable ones to survive.

Predictions of the Theory of Invasive Technologies

Let me show some testable implications of the theory of invasive technologies for technological evolution:

- Technological change =*f*(invasive technologies)
- Rate of growth of invasive technology i in space S > 2 × rate of growth of alternative technologies *j* in space S, *j*=1, …, *m*
- Invasive technology (*i*) is better adapted than alternative technologies (*j*) in S if and only if (*i*) is able to spread, survive, and produce new innovations in S more than (*j*).

Interrelationships of invasive technologies in the innovation ecosystem with related impact are in Figure 1.

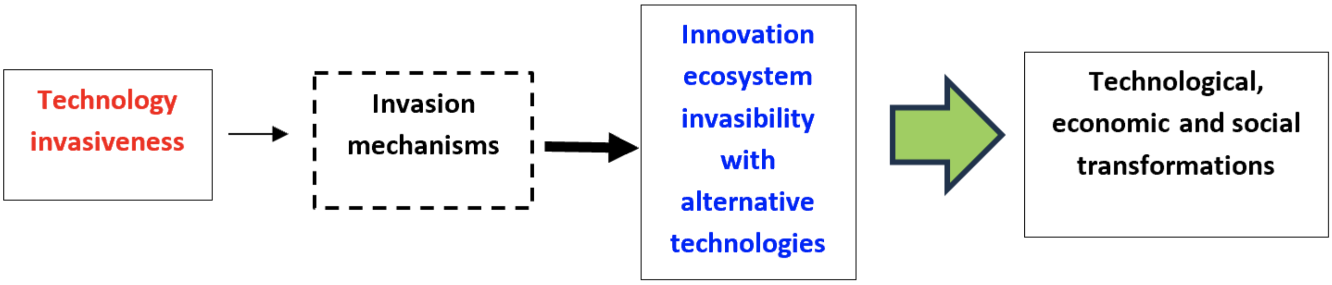

Figure 1. A Schematic Diagram of Invasive Technologies.

4.3. Research Setting to Test the Theoretical Prediction: Transformer Technologies

The predictions of the proposed theory of invasive technologies are verified empirically in some main technologies. In the context of Artificial Intelligence (AI) R&D of new products and processes, this study focuses on the new technology of transformer architecture, a new type of neural network, described by Vaswani et al. (2017). Traditional Recurrent Neural Networks (RNNs) are powerful tools, but they have limitations, such as slow training and not retaining old connections well, among others. Instead, the new architecture of transformer technology is based on three powerful elements: a) self-attention; b) positional embeddings; and c) multi-head attention. Unlike traditional RNN models, transformer models are designed to learn contextual relationships between words in a sentence or text sequence through the mechanism of self-attention, which allows the model to weigh the importance of different words in a sequence based on their context (Menon, 2023). Transformer models have revolutionized some research fields, such as Natural Language Processing (NLP), for tasks of language modeling, text classification, question answering, sentiment analysis, computer vision, spatiotemporal modeling for video analysis or time series data, and others (Menon, 2023). In these domains, a critical advantage of transformer models is the ability to process input sequences in parallel, which makes them faster than RNNs for many NLP tasks (Dell, 2023). One of the main radical innovations in transformer technology is the development of large-scale, pretrained language models, referred to as Generative Pretraining Transformers (GPTs), such as OpenAI's GPT series, from GPT-1 in 2018 to ChatGPT-4 in 2023, capable of generating human-like content (OpenAI, 2015, 2022); Google's Bidirectional Encoder Representations from Transformers (BERT) model (Devlin et al., 2018); Microsoft Copilot (Mehdi, 2023); etc. These pretrained models can be used for specific NLP tasks with reduced additional training data, making them highly effective for a wide range of NLP applications, such as (cf. Assael et al., 2022; Kariampuzha et al., 2023):

- machine translation
- document summarization
- document generation
- named entity recognition
- biological sequence analysis
- writing computer code based on requirements expressed in natural language
- video understanding
- computer vision, protein folding applications, etc.

Overall, then, advances in computer science have led to the advent of the large language model (LLM, Bowman, 2023). In this domain, the new technology of transformers is directed at modeling some activities of the human brain and has led to the new research field of generative AI — software that can create plausible and sophisticated text, images, and computer code at a level that mimics human ability (Pinaya et al., 2023; Tojin et al., 2023). Transformer architecture has revolutionized the field of LLM with main applications in NLP and generative AI that have generated radical innovation in GPT and its continuous incremental improvements directed at shaping the landscape of generative AI with consequential technological and social change. The technological analysis of the main technologies of transformer models can clarify basic characteristics of the evolution of new technologies and radical innovations, having a pervasive behaviour that supports a paradigm shift in technological fields and society (Dosi, 1988).

4.4. Study Design: Logical Structure of Searches and Measures

We assume that Transformer architecture is an invasive technology and to generalize the scientific concept with backward induction, we also analyze a previous technology, CNN, to assess its behaviour. A comparative analysis of these main technologies in Large Language Models can support general characteristics and properties of invasive technologies that can explain technological evolution and change.

- Logical Structure of Search

In order to detect with accuracy the invasive technologies under study in the database Scopus (2024), we define the General Domain D for queries to detect scientific documents:

D = ("machine learning" OR "data science" OR "artificial intelligence").

After that, we refine the Domain for the two technologies under study to analyze predatory research fields.

- Transformers, period under study 2017-2023
  Domain Restricted for Transformers is called DTR
  DTR = ("machine learning" OR "data science" OR "artificial intelligence")
  AND
  ("large language models" OR "LLM" OR "Natural Language Processing" OR "Natural Languages" OR "Sentiment Analysis" OR "Text Mining" OR "Question Answering Systems" OR "Semantic Web" OR "Chatbot" OR "Knowledge Representation" OR "Natural Language Understanding" OR "Text-mining" OR "Opinion Mining" OR "Topic Modeling" OR "Word Embedding")
  Or
  DTR = (D) AND ("large language models" OR "LLM" OR "Natural Language Processing" OR "Natural Languages" OR "Sentiment Analysis" OR "Text Mining" OR "Question Answering Systems" OR "Semantic Web" OR "Chatbot" OR "Knowledge Representation" OR "Natural Language Understanding" OR "Text-mining" OR "Opinion Mining" OR "Topic Modeling" OR "Word Embedding")
  In order to detect the impact of Transformers (TRF) in science that is also used with other terms, the query is given by: TRF = (DTR) AND ("bert" OR "chatgpt" OR "transformer" OR "attention mechanism"). This set TRF includes the technology with predatory behaviour.
  The complement of set TRF is TRF^C:
  TRF^C = (DTR) AND NOT ("bert" OR "chatgpt" OR "transformer" OR "attention mechanism").
  This set includes the technologies that have been predated by TRF.
  Of course, TRF + TRF^C = DTR
- Convolutional Neural Networks, in short CNN, period under study before 2017, the year of the emergence of Transformers
  The general domain is D, as defined above, but in order to detect the science dynamics of CNN, we refine the search with a restriction considering the field in which CNN operates. The keywords are stopped when the restricted set has a

marginal increase of scientific documents.

The domain restricted for CNN is called DCNN:

DCNN = ("machine learning" OR "data science" OR "artificial intelligence")

AND

("computer vision" OR "image recognition" OR "Image Processing" OR "Object Detection" OR "Image Segmentation" OR "Image Enhancement" OR "Object Recognition" OR "Image Analysis" OR "Image Classification" OR "Images Classification" OR "Face Recognition" OR "Machine Vision" OR "Image Interpretation" OR "Gesture Recognition" OR "Machine-vision" OR "Augmented Reality")

Or

DCNN = (D) AND ("computer vision" OR "image recognition" OR "Image Processing" OR "Object Detection" OR "Image Segmentation" OR "Image Enhancement" OR "Object Recognition" OR "Image Analysis" OR "Image Classification" OR "Images Classification" OR "Face Recognition" OR "Machine Vision" OR "Image Interpretation" OR "Gesture Recognition" OR "Machine-vision" OR "Augmented Reality")

In order to detect the impact of CNN, the query is given by:

CNN = (DCNN) AND ("convolutional neural network" OR "CNN"). This set CNN includes the technology with predatory behaviour.

The complement of set CNN is CNN^C is

CNN^C = (DCNN) AND NOT ("convolutional neural network" OR "CNN"). This set included the technologies that have been predated by CNN.

Moreover, CNN + CNN^C = DCNN

- Measures and Sources of Data

This study uses the number of patents concerning research topics and technologies under study. Data are from Scopus (2023), downloaded on November 9, 2023.

- Samples

In particular, the study considers the following sample of data, detected using the previous logic:

- Set of Transformers TRF: 8,908 patents (all data available from 2016 to 2023).
- Complement of set TRF, TRF^C: 79,268 patents (all data available from 2016 to 2023).
- Set of CNN: 69,599 patents (all data available from 1995 to 2023).
- Complement set of CNN, CNN^C: 181,231 patents (all data available from 1995 to 2023).

- Data and Information Analysis Procedures

Let Patents(TRF) = number of patents of Transformers, having invasive behaviour.

Let Patents(TRF^C) = number of patents in other technologies in domain of TRF

Let DTRF = Patents(TRF) + Patents(TRF^C), the total number of patents in the domain of technologies of Large Language Models.

$$\alpha = \frac{\text{Patents }(TFR)}{DTFR} \quad \beta = \frac{\text{Patents}\left(TFR^C\right)}{DTFR} \quad \alpha + \beta = 1$$

Let Patents(CNN) = number of patents of CNN with invasive behaviour.

Let Patents(CNN^C) = number of patents of other technologies in the domain of CNN.

Let DCNN = Patents(CNN) +Patents(CNN^C), the total number of patents in the domain of technologies of Large Language Models.

$$\delta = \frac{\text{Patents }(CNN)}{DCNN} \quad \varepsilon = \frac{\text{Patents}\left(CNN^C\right)}{DDCNN} \quad \delta + \varepsilon = 1$$

These shares of the spatial growth of invasive technologies in the domain are calculated over time and visualized graphically.

After that, the temporal growth of these technologies over time is analyzed with a rate of growth compounded continuously: *r*. In this case, the function of patent development is exponential:

$$\text{Patents }_t = \text{ Patents }_0 e^{rT}$$

Hence, $\frac{\text{P}_{\text{atents } t}}{\text{P}_{\text{atents } 0}} = e^{rT}$, where *e* is the base of the natural logarithm (2.71828…)

$$\text{Log} \frac{\text{Patents }_t}{\text{Patents }_0} = rT$$

$$r = \frac{\text{Log} \frac{\text{Patents }_t}{\text{Patents }_0}}{T}$$

Where

- P_0 is the number of patents at time 0,
- P_t is the number of patents at time t.
- T= t-0
- r= rate of exponential growth of technology from 0 to t period.

Trends of invasive technology *i* at *t* are analyzed with the following model:

$$\text{Log}_{10} y_{i,t} = a + b \text{ time} + u_{i,t}$$

- y_t is the number of patents of invasive technologies
- t = time
- u_t = error term
- (a = constant; b = coefficient of regression)

5. Empirical Evidence: Test of Prediction in Invasive Technologies

5.1. *Pattens of Temporal and Morphological Change*

Table 1. Parametric estimates of the relationships based on patents

Dependent variable Publications	Constant α	Coefficient β	R^2	F	Period
Log10 Patents Transformers	1.30***	0.30*** (0.016)	0.98 (0.105)	339.95***	2016-2023
Log10 Patents not transformers	3.34***	0.13*** (0.017)	0.91 (0.107)	57.71***	
Log10 Patents CNN	-0.87***	0.16*** (0.010)	0.92 (0.431)	292.05***	1995-2023
Log10 Patents not CNN	1.61***	0.10*** (0.003)	0.98 (0.125)	1227.66***	

*Note: *** p<0.001; Explanatory variable: time; period is from the starting year of the patent to 2023 (last year available); In round parentheses, the Standard Error. The F-test is based on the ratio of the variance explained by the model to the unexplained variance. R^2 is the coefficient of determination.*

Table 1 shows a regression analysis of the estimated relationship based on patents over time, using a linear model. R^2 is remarkably high in all models, showing a high goodness of fit. The F-test is significant with a p-value <.001. The estimated coefficient of regression suggests that transformers, as an invading technology, have a growth rate of 0.30 (p-value 0.001), which is more than double that of other technologies operating in the same domain (0.13, p-value 0.001). Moreover, the most interesting finding is that the growth rate of invading transformers in the space of science and technology, compared to the other radical technology of CNN, is almost double (0.16, p-value 0.001). This result suggests that the invasive power of transformers is of high intensity, having pervasive diffusion and a more drastic impact to generate the conditions for a main radical scientific and technological change in science and technology (for visual representation, see Figures 2 and 3).

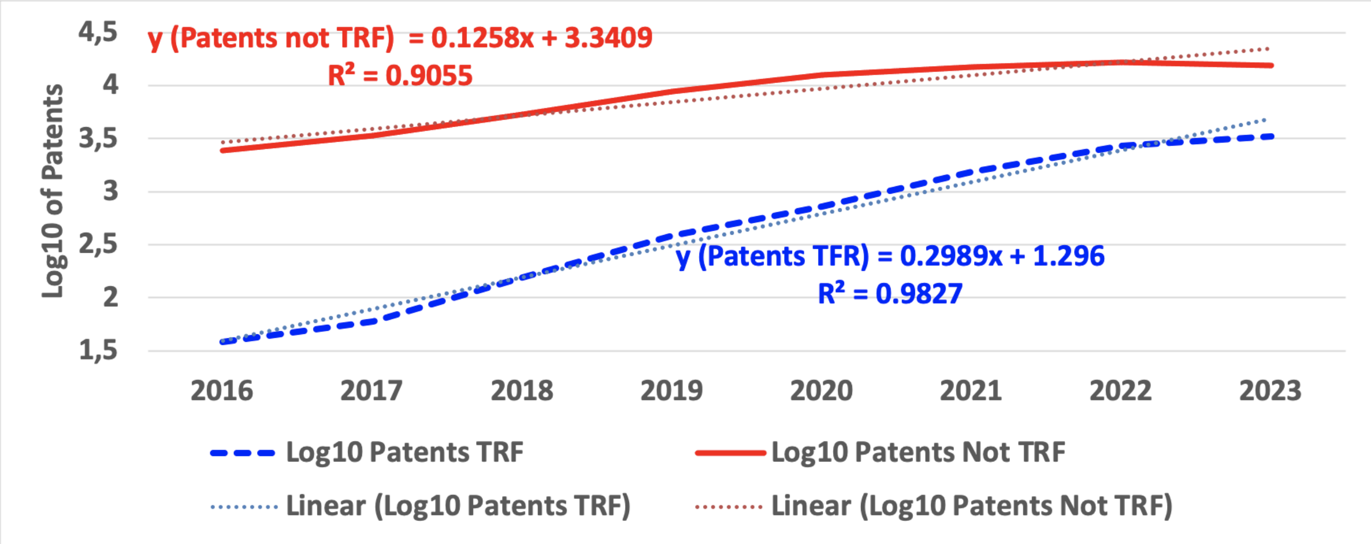

Figure 2. Estimated relationships for the temporal evolution of Transformers compared to the overall domain of Large Language Models (Patents), 2016-2023 period. The dotted line indicates the dynamics of invasive technology; the continuous line indicates the dynamics of other technologies.

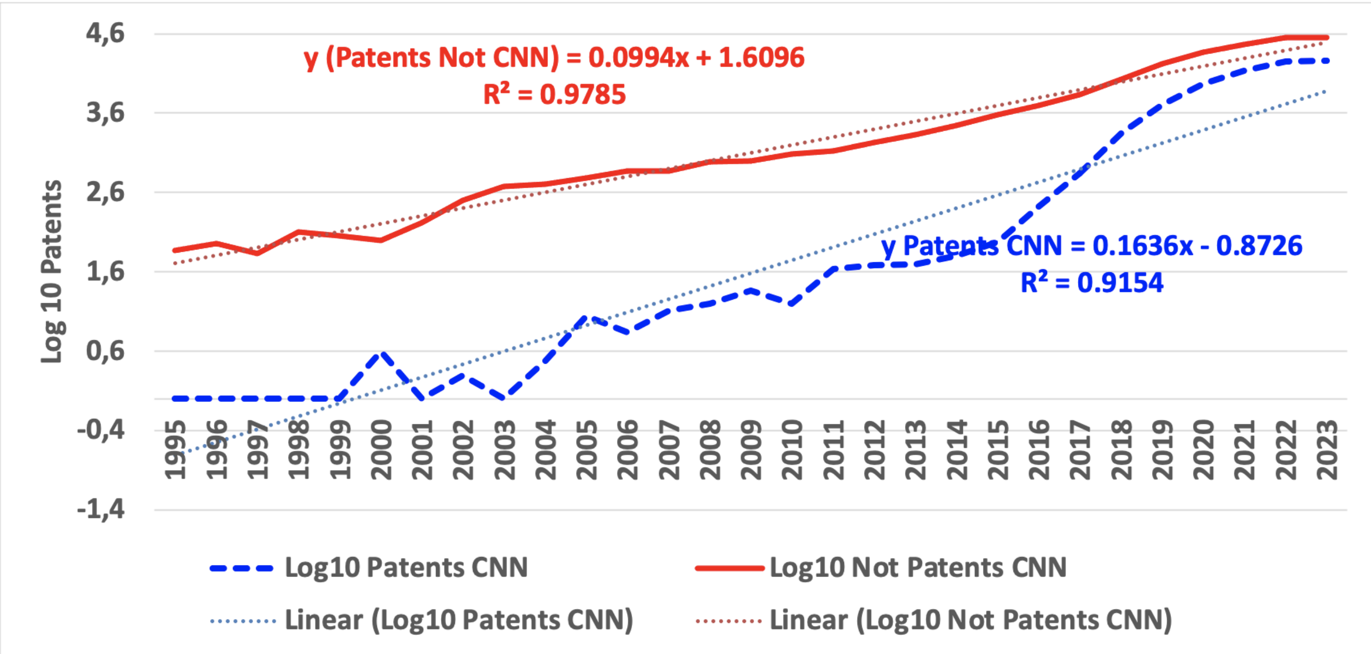

Figure 3. Estimated relationships for the temporal evolution of CNN compared to the overall domain of Large Language Models (Patents), 1995-2023 period. The dotted line indicates the dynamics of invasive technology; the continuous line indicates the dynamics of other technologies.

Table 2. Exponential rate of growth in Large Language Models of predators and preys

	Transformers	Domain excluded Transformers
Patents	Rate%	Rate %
r^{TRF} = Exponential growth 2016-2023	55.82	23.02
r''^{TRF} = Exponential growth 2021-2023	25.81	0.76
	CNN	Domain excluded CNN
Patents	Rate%	Rate %
r'^{CNN} = Exponential growth 1995-2023	33.84	36.11

Using the exponential equation to calculate the growth rate of technologies under study, it confirms that the growth rate of the invading technology of transformers is about 56% versus 23% of alternative technologies in space (more than double), and it is considerably higher than the previous technology of CNN, having about 34% (Table 2). This result confirms the invasive behaviour of transformer technologies in the space of LLM, based on rapid and strong diffusion. Considering the invasive dynamics of transformers, based on the share of patents of transformers on the total in the space of LLM, in about 7 years, it has a rapid diffusion that invades the space of other technologies in the related domain, changing the ecosystem of LLM with pervasive application in generative AI with manifold radical innovations that generate technological and social change (Figure 4). The share of patents in CNN technologies in 2023 is higher than transformer technology, but the accumulation of knowledge started in 1995, compared to Transformers that started in 2017 (Figure 5).

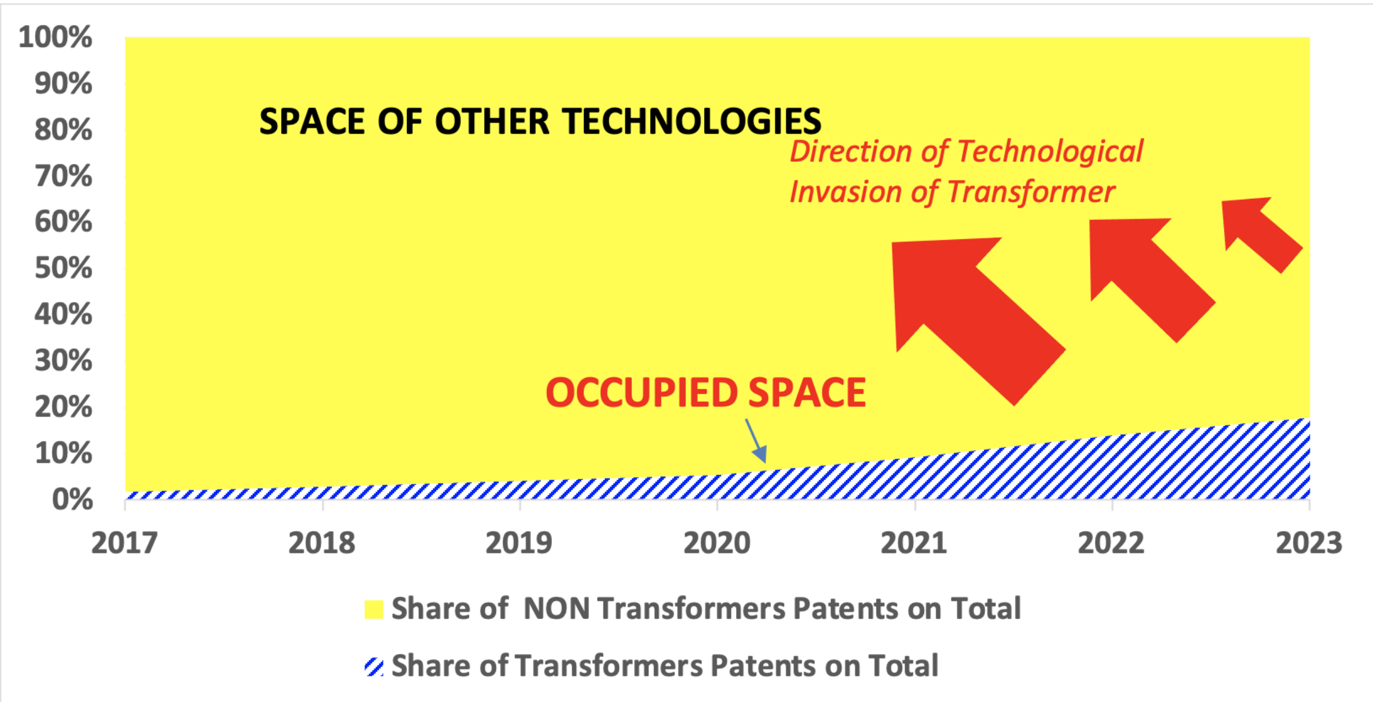

Figure 4. Patterns of morphological change in the domain of large language models generated by the emerging technology of transformers (Patents). Large arrows indicate the direction of technological invasion.

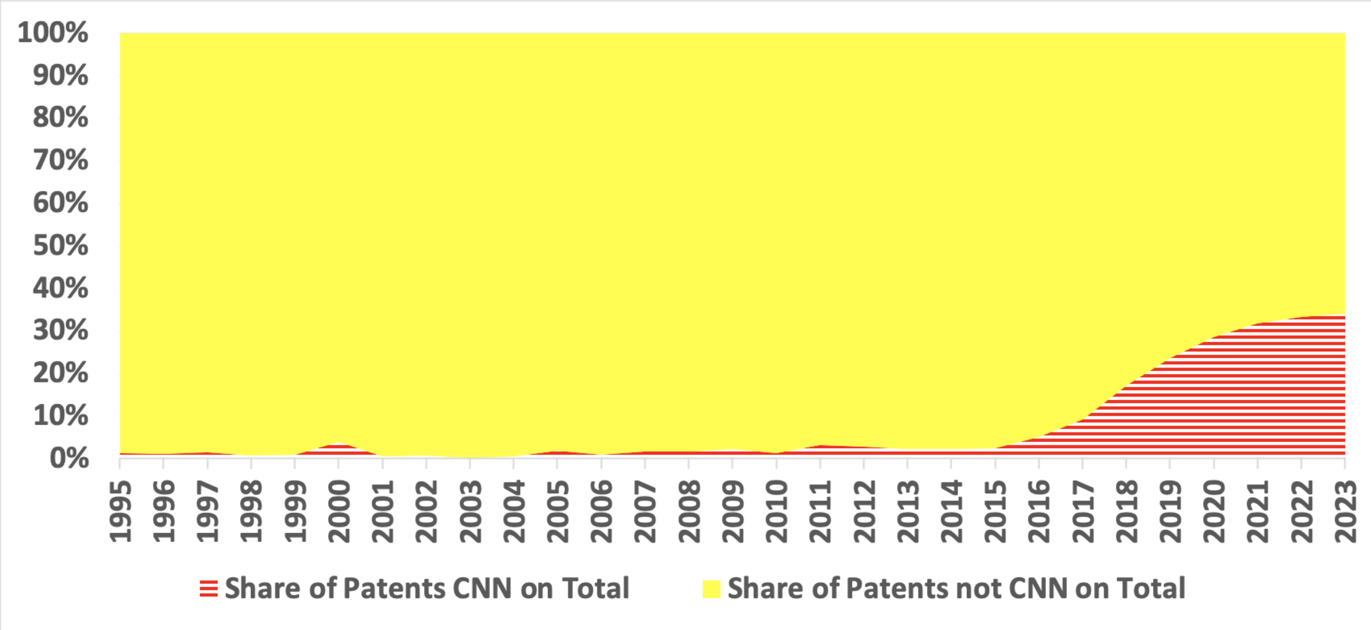

Figure 5. Patterns of morphological change of CNN in the domain of large language models generated by (Patents).

6. Discussions

6.1. *Explanation of Empirical Evidence of Invasive Technologies in Reference to Previous Literature*

The emergence of transformer technology is due to the interaction and convergence of competencies from mathematics and model design in neural networks. Transformer architecture was introduced in the context of natural language processing (NLP), but they have shown to be versatile and powerful, finding new applications in diverse fields such as computer vision, speech recognition, etc. In the realm of neural networks, the Transformer architecture has emerged as a transformative force, initially revolutionizing natural language processing and subsequently finding applications in diverse domains. Before transformers, recurrent neural networks (RNNs) had many limitations, but a main breakthrough is the introduction of the self-attention mechanism, which intuitively mimics cognitive attention. It calculates "soft" weights for each word, which can be computed in parallel in transformer architecture, unlike sequentially by RNNs. Attention was developed to address the weaknesses of leveraging information from the hidden outputs of recurrent neural networks. In short, transformers' large language models removed the recurrent neural network and relied heavily on the faster parallel attention scheme (Tyagi, 2023). A basic driver of the invasive behaviour of transformers is the interaction with different research fields and technologies (Coccia, 2019, 2019a). In particular, invasive behaviour emerges and rapidly spreads by interacting in complex systems with parasitic or symbiotic relationships (Coccia and Watts, 2020). The speed at which these invasive technologies expand their range is a fundamental parameter to explain technological evolution and change (cf., Schreiber and Ryan, 2011). Knowledge of the estimated speed, calculated with the empirical analysis here, enables us to predict the ability of these technologies to be a dominant one and support technological and social change. Moreover, understanding its rate of spread is also important to show how the spread of a technology can evolve. Using temporal and spatial models of evolution, based on data of patents, statistical analyses reveal that the rate of growth of these path-breaking technologies has an accelerated rate of patents compared to alternative technologies. This result suggests that the interaction of path-breaking and emerging technologies is basic to accelerate co-evolution for laying the foundations for technological change in society (Coccia, 2019, 2020, 2020a, b, c). Scholars have shown that interaction among technologies can support technological evolution, and this result here is consistent with one of the multi-mode interactions 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 invasive technologies. In the case under study of transformers, the interaction generates high growth rates and a symbiotic-dependent evolution between technologies. The concept of symbiosis is closely related to that of mutualism (it is any type of relationship in which each technology benefits from the activity of the other; cf., Coccia, 2019) and to commensalism, which is any type of relationship between two technologies where one benefits from the other without affecting it (Coccia and Watts, 2020). With respect to the technological systems of interest here, results suggest a symbiosis of transformers that shows versatility in interactions with other inter-related technologies. The interaction of technologies in the vast domain of artificial intelligence can generate synergistic combinations and foster major innovations in LLMs, which are currently progressing at a rapid rate, such as ChatGPT and similar ones. The progress of this interaction can become self-catalyzing and can give the means to deal successfully with challenges in manifold fields and industries, opening completely new opportunities in markets (such as in AI, Burger et al., 2023; Krinkin et al., 2023; Roco and Bainbridge, 2002).

Moreover, transformers have invasive behaviour because they have the characteristics to be a General Purpose Technology (GPT) in the vast domain of applications in Artificial Intelligence (Coccia, 2020). The path-breaking technology of transformers is mainly of transformative nature and generates creative destruction (Calvano, 2007), which makes prior products/processes and knowledge obsolete (cf. Colombo et al., 2015). 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." (cf. Lipsey et al., 2005). Invasive technologies, as GPTs, exert a pervasive impact across firms, industries, and permeate the overall economy of nations. Bresnahan and Trajtenberg (1995, pp. 86–87) show that GPTs have a tree-like structure with new technology located at the top of the tree and all derived technologies represented at the bottom of the tree, radiating out towards every sector of the economy. In fact, transformer architecture, as GPTs, generates clusters of innovations in several industries because they are basic processes/components/technical systems for the structure of various families of products/processes that are made quite differently, supporting co-evolutionary pathways. Bryan et al. (2007, p. 41) argue that: "co-evolution can lead to reduced product development costs and increased responsiveness to market changes". The manifold applications of transformers as GPTs are driven by firms (such as OpenAI, Microsoft, Google Brain, etc.) to maximize profit and/or to exploit the position of a (temporary) monopoly and/or competitive advantage in sectors and/or industries (Calvano, 2007; Coccia, 2015, 2016). In general, transformers as GPTs are characterized by: "pervasiveness, inherent potential for technical improvements, and 'innovational complementarities', giving rise to increasing returns-to-scale, such as the steam engine, electric motor, and semiconductors" (Bresnahan and Trajtenberg, 1995, p. 83, original emphasis). Moreover, Jovanovic and Rousseau (2005, p. 1185) show that the distinguishing characteristics of a GPT are:

1. Pervasiveness: A GPT should propagate to many sectors.
2. Improvement: A GPT should reduce the costs of its adopters.
3. Innovation spawning: A GPT should produce new products and processes (cf. also Bresnahan and 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 that fit the transformer architecture to generate innovations (cf. Coccia, 2012a, 2012b, 2017a, 2017). Overall, then, transformers as GPTs are complex technologies that support product/process innovations in several sectors for corporate, industrial, economic, and social change (Coccia, 2015; cf. Coccia, 2012, 2012a, 2014, 2014a, 2016, 2017).

6.2. *Deduction form Invasive Behaviour of Technologies*

Empirical research to test the prediction of invasive technologies suggests some main deductions of invasive technologies for possible generalization:

- Changes over time. Current invasions of new technologies are the result of the interplay of past events and processes (Kueffer, 2010b; Pyšek et al., 2010; Essl et al., 2011). The extension of knowledge in these fields is basic for resolving fundamental questions in invasion ecology of technologies and is associated with the accumulation of manifold and detailed information on invasions of particular technologies in different industries and over time.
- A basic invasion mechanism of transformer technology can be the hypothesis of unused resources. Large datasets gained from different technologies can pave the way for addressing interactions and testing the application of the proposed framework here more effectively.
- Invasions of new technologies can generate a change in the behaviour of a technology following its introduction in designing new products and processes and spreading them.

7. Concluding Remarks

Socioeconomic forces of the knowledge economy are changing the foundations of economies and societies and accelerating the rate at which new technologies are being introduced with invasive behaviour and pervasive diffusion over space. This study proposes, for the first time, the invasive behaviour of technologies. The successful technology invaders can have devastating impacts on human society and the structure of modern economies. To manage these impacts, it is essential to understand the rate of range expansion—the invasion speed—of these technology invaders. Here, we estimate and analyze invasion speeds to provide a general framework for invasive technologies in a variable environment experiencing rapid changes. This study tests the theories of invading technologies, focusing on transformative technologies in AI that have unparalleled growth at the expense of other technologies, creating basic conditions to generate a drastic scientific change in LLM and consequential radical technological change with main effects on economic and social systems in the not-too-distant future. This specific behaviour of invasive technologies fosters rapid diffusion, destroys other technologies, and captures their space. This aspect in the literature leads to technological substitution.

Norton and Bass (1987) consider that a new product or process generation can replace a prior one. This process between different technologies is based on a competition of performance and effectiveness. Fisher and Pry (1971) modeled the diffusion of a new product becoming a substitute for a prior one (cf., Utterback and Brown, 1972). Other scholars have explained this competition as a predator and preys; the new product is a predator of current products (prey; Utterback et al., 2019). Invasive technologies have the power to disrupt, destroy, and make obsolete established competencies (Christensen et al., 2015, 1997; Coccia, 2020). What this study adds is that the invasive behaviour of new technology is more drastic than that of a competitor or predator technology, as verified with transformer architecture. What is the cause that drives Transformer architecture to be an invasive technology? One of the explanations is a specific current interest in the community of scholars (Sun et al., 2013). This aspect may be explained by the emergence of social groups of scientists in these topics as the driving force behind the evolution of this emerging and disruptive technology in a network of inter-related technologies and research fields (Crane, 1972; Coccia et al., 2024; Guimera et al., 2005; Wagner, 2008). In this context, the rapid evolution of invasive technology paves the way for the development of other technologies in spatial-temporal areas by "expanding the adjacent possible" (Kaufman, 1996).

7.1. *Theoretical Implications*

The predictions of our theoretical framework of invasive technologies are borne out in the phenomena investigated, paving the way to a better understanding and control of innovation processes in a knowledge economy.

Properties of Invasive Technologies

Let InvT*i* = Invasive technology *i*

Let Pr*j* = other technologies in the inter-related domain D;*j*=1, 2, …, *m*

(ITi, Pr*j*) ⊆ D

t = year of emergence of IT*i*

σ*i* = growth rate of InvT*i*

τ *j* = growth rate of Pr *j*

Invasive technology IT*i* in the domain D is when from t to*t*+*n:*

- IT*i* has a very rapid growth
- IT*i* disrupts the context of other technologies
- IT*i* invades and captures the space of other technologies

Moreover, other characteristics of invasive technologies are:

- Rapid growth
- Adaptation to a wide range of market applications and environmental conditions

- Prolific diffusion in manifold technical systems
- Associations with manifold activities of humans

These results can be the basis for an emerging science of invasive technologies that can explain technological, economic, and social change in three main scientific directions:

1. Invasiveness of technologies;
2. Invasibility of innovation ecosystems; and
3. Recurrent (patterns of the technologies) × (ecosystem interactions) that may support a technological invasion syndrome based on a set of concurrent aspects that usually form an identifiable pattern. A science of invasive technologies can encompass "typical recurrent associations of technologies and invasion dynamics with particular invasion contexts such as invasion phases, invaded environments, and socioeconomic contexts" (cf., Kueffer et al., 2013). We expect that a resulting theory of technological invasions will need to be conceived as a somewhat heterogeneous conglomerate of elements of varying generality and predictive power: laws that apply to well-specified domains, general concepts and theoretical frameworks that can guide thinking in research and management, and in-depth knowledge about the drivers of particular invasions of technologies in specific industries or across sectors.

7.2. *Managerial and Policy Implications*

In all these systems of invasive technologies, surprisingly similar patterns emerge based on two contrasting forces that can have managerial implications: the tendency to retrace already explored avenues (exploit) and the inclination to explore new possibilities. Policymakers and R&D managers can use the findings here to make efficient decisions regarding the sponsoring of specific trajectories with a high rate of growth to foster technology transfer with fruitful effects for boosting the next economic and industrial change. These managerial approaches can be explained within the framework of the expansion of the adjacent possible, in which the restructuring of the space of possibilities is conditional on the occurrence of radical innovations. Proposed theory and empirical findings can guide an ambidexterity strategy of innovation management based on exploration activities when the rate of growth and uncertainty in research fields and technology are higher, whereas an exploitation approach to innovation strategy is appropriate when the rate of growth is lower, with consequentially more stable technological trajectories. Organizations can apply an ambidexterity strategy of innovation management by balancing exploration and exploitation approaches, which allows the organization to be adaptable to turbulent environments and achieve and sustain a competitive advantage (Duncan, 1976; March, 1991; Raisch and Birkinshaw, 2008). In particular, the findings here suggest that in the presence of a higher rate of growth and higher indeterminacy, organizations can apply an innovation strategy of exploration based on search, risk-taking, experimentation, selection, discoveries, and flexibility between different technological pathways. However, organizations that focus only on exploration face the risk of wasting resources on research topics and emerging technologies that may fail and never be developed, so a stage-gate model can reduce failure risk and foster the development of new technology (Coccia, 2023). Instead, technologies with a lower rate of growth suggest an innovation strategy of exploitation based on refinement, efficiency, implementation, execution, and production in more stable technological trajectories and directions.

7.3. *Limitations and Development of Future Research*

This study shows, for the first time to our knowledge, the behaviour of an invasive technology to explain some properties of technological and scientific change in knowledge economies. One of the significant aspects of explaining invading technologies is to estimate and analyze their rates of spread and behaviour. The speed at which a technology expands its range is a fundamental parameter in explaining technological invasion and consequential evolution. Knowledge of this speed enables us to predict the ability of a technology to become a dominant technology and to generate radical and incremental innovations in a space with manifold alternative technologies. This study analyzes the invasive behaviour of transformer technologies in AI that has unparalleled growth at the expense of other technologies, creating basic conditions to generate a drastic scientific change in LLM and consequential radical technological change with major effects on economic and social systems in the not-too-distant future.

These conclusions are, of course, tentative. This study provides some interesting but preliminary results in these complex fields of emerging technologies. However, there are some limitations to address in future studies, which can be summarized as follows. Many fundamental questions in the science of invasive technologies can only be answered through integrative studies, such as research that encompasses comprehensive studies of invasions of a particular technology in specific fields, comparative studies of invasions of the same technologies across multiple fields and industries, and integrating diverse information about a particular technology to analyze invasive behaviour with context dependencies. In a proposed theory of invasion technology, in-depth analysis of the invaded innovation ecosystem focuses mostly on the scientific area dominated by a single dominant invader technology (transformer). However, studies of the multifarious and longer-term dynamics of innovation ecosystems affected by multiple technology invaders are mostly lacking. Such studies are, however, important to understand shifts in the dominance of invading technologies, possibly leading to interactions among multiple invaders. In the context of invaded ecosystems, an emerging challenge is also to understand the role of gradual changes in technologies and environmental factors in determining invasion trajectories (e.g., Smith et al., 2009). Hence, it is interesting to compare the invasive behaviour of the same technologies across multiple industries and research fields, to assess if ‘invasiveness’ and effects on the environment of technologies may be highly variable at different sites. Such differences in invasion dynamics of technologies between industries might stem from (1) the variability of the architecture of a technology between industries – through product differentiation; (2) technologies and environment interactions. In analogy with biology, the impacts of invasive technologies are strongly co-shaped by the relation of (technologies) × environment interactions (Hulme et al., 2012; Pyšek et al., 2012), which can only be understood through comparative studies across industries (cf., Kueffer et al., 2013). More studies that compare the technology in native research fields or sectors and invaded ranges are needed (van Kleunen et al., 2010), because such insights form the baseline necessary for drawing conclusions about the importance of specific technologies in invasions (Parker et al., 2013). Therefore, given the variation in the performance of a technology within both native and invaded research fields, studies that compare data only from one research field are very likely to arrive at spurious conclusions. Thus, synthetic analyses in invasion science for technologies must be constrained to appropriate subsets of invasions, rather than seeking universal explanations (Pyšek & Richardson, 2007; Jeschke et al., 2012; Kueffer, 2012). A future idea is to verify if technological superiority or flexibility applies to all invasions (e.g., Daehler, 2003; Blumenthal et al., 2009; Cavaleri & Sack, 2010; Chun et al., 2010; Jeschke et al., 2012a; Moles et al., 2012). For instance, characteristics that are most frequent among invasive technologies and general disruptive technologies in markets might not be relevant for predicting invasive technologies within a specific industry. Other limitations are that scientific outputs and research topics can only detect certain aspects of the ongoing dynamics of technology, and the next study should apply complementary analysis; confounding factors (e.g., the level of public and private R&D investments, international collaboration, etc.) affect the evolution of new technologies, and these aspects have to be considered in future studies to improve data gathering for technological analyses.

In short, there is a need for much more detailed research into the investigation of the role of invasive technologies to clarify evolutionary patterns of technologies in society. Despite these limitations, the results here clearly illustrate that invasive technologies can clarify basic characteristics of technological, economic, and social change. These findings can encourage further theoretical exploration in the terra incognita of invasive technologies within and between scientific and technological domains that have rapid change in the new digital era. These aspects are basic for improving the prediction of evolutionary pathways in emerging and disruptive technologies and supporting R&D investments towards new technologies and innovations with a high potential for growth and impact on the socioeconomic system. However, a comprehensive explanation of the sources and diffusion of invasive technologies to explain technological change is a difficult topic due to manifold complex and inter-related factors in the presence of a changing and turbulent environment, such that Wright (1997, p. 1562) aptly claims: “In the world of technological change, bounded rationality is the rule.”

Acknowledgments

I would like to thank E. Borriello (ASU) for suggestions and discussions on methodology in preliminary versions of the paper. All data are available on Scopus (2024). The author declares that he has no known competing financial interests or personal relationships that could influence the work reported in this paper. This study has no funders. The usual disclaimer applies.

Bibliography

- Abernathy, W. J., & Clark, K. B. (1985). Innovation: Mapping the winds of creative destruction.*Research Policy, 14*(1), 3-22. https://doi.org/10.1016/0048-7333(85)90021-6
- Adner, R. (2002). When are technologies disruptive: A demand-based view of the emergence of competition.*Strategic Management Journal, 23*, 667.
- Adner, R., & Zemsky, P. (2005). Disruptive technologies and the emergence of competition.*The RAND Journal of Economics, 36*(2), 229-254.
- Amarlou, A., & Coccia, M. (2023). Estimation of diffusion modelling of unhealthy nanoparticles by using natural and safe microparticles. *Nanochemistry Research, 8*(2), 117-121. https://doi.org/10.22036/ncr.2023.02.004
- Anastopoulos, I., Bontempi, E., Coccia, M., Quina, M., & Shaaban, M. (2023). Sustainable strategic materials recovery,

what's next? _Next Sustainability, VSI: Sustainable strategic materials recovery_Editorial, 100006. https://doi.org/10.1016/j.nxsust.2023.100006

- Arthur, B. W. (2009). *The nature of technology: What it is and how it evolves* Allen Lane–Penguin Books.
- Assael, Y., Sommerschield, T., Shillingford, B., Bordbar, M., Pavlopoulos, J., Chatzipanagiotou, M., Androutsopoulos, I., Prag, J., & de Freitas, N. (2022). Restoring and attributing ancient texts using deep neural networks. *Nature, 603*(7900), 280–283. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8907065
- Barton, C. M. (2014). Complexity, social complexity, and modeling. *Journal of Archaeological Method and Theory, 21*, 306–324.
- Basalla, G. (1988). *The history of technology*. Cambridge University Press.
- Bettencourt, L. M., Kaiser, D. I., & Kaur, J. (2009). Scientific discovery and topological transitions in collaboration networks. *Journal of Informetrics, 3*, 210–221.
- Blumenthal, D. A. (2006). Interactions between resource availability and enemy release in plant invasion.*Ecology Letters, 9*, 887–895.
- Boccaccio, C., & Comoglio, P. (2006). Invasive growth: A MET-driven genetic programme for cancer and stem cells. *Nature Reviews Cancer, 6*, 637–645. https://doi.org/10.1038/nrc1912
- Bowler, D. E., & Benton, T. G. (2005). Causes and consequences of animal dispersal strategies: Relating individual behaviour to spatial dynamics. *Biological Reviews of the Cambridge Philosophical Society, 80*(2), 205–225. https://doi.org/10.1017/s1464793104006645
- Bowman, S. R. (2023). Eight things to know about large language models.*arXiv:2304.00612 [cs.CL]*. https://arxiv.org/abs/2304.00612
- Bresnahan, T. F., & Trajtenberg, M. (1995). General purpose technologies: 'Engines of growth'?*Journal of Econometrics, Annals of Econometrics, 65*(1), 83–108.
- Bryan, A., Ko, J., Hu, S. J., & Koren, Y. (2007). Co-evolution of product families and assembly systems.*CIRP Annals - Manufacturing Technology, 56*(1), 41–44. https://doi.org/10.1016/j.cirp.2007.05.012
- Burger, B., Kanbach, D. K., Kraus, S., Breier, M., & Corvello, V. (2023). On the use of AI-based tools like ChatGPT to support management research. *European Journal of Innovation Management, 26*(7), 233-241. https://doi.org/10.1108/EJIM-02-2023-0156
- Calabrese, G., Coccia, M., & Rolfo, S. (2005). Strategy and market management of new product development: evidence from Italian SMEs. *International Journal of Product Development, 2*(1–2), 170–189. https://doi.org/10.1504/IJPD.2005.006675
- Calvano, E. (2007). Destructive Creation. *SSE/EFI Working Paper Series in Economics and Finance*, (653).
- Cavaleri, M. A., & Sack, L. (2010). Comparative water use of native and invasive plants at multiple scales: a global meta-analysis. *Ecology, 91*, 2705–2715.
- Cavallo, E., Ferrari, E., & Coccia, M. (2015). Likely technological trajectories in agricultural tractors by analysing innovative attitudes of farmers. *International Journal of Technology, Policy and Management, 15*(2), 158–177. https://doi.org/10.1504/IJTPM.2015.069203
- Christensen, C. (1997). The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail. Harvard

Business School Press.

- Christensen, C. (2006). The ongoing process of building a theory of disruption. *Journal of Product Innovation Management, 23*, 39–55.
- Christensen, C., Raynor, M., & McDonald, R. (2015). What is disruptive innovation? *Harvard Business Review*, December, 44-53.
- Christensen, C. M. (1997). The Innovator's Dilemma. Harvard Business School Press.
- Chun, Y. J., van Kleunen, M., & Dawson, W. (2010). The role of enemy release, tolerance and resistance in plant invasions: linking damage to performance. *Ecology Letters, 13*, 937–946.
- Coccia, M. (2003). Metrics of R&D performance and management of public research labs. In *IEMC '03 Proceedings. Managing Technologically Driven Organizations: The Human Side of Innovation and Change* (pp. 231-235). https://doi.org/10.1109/IEMC.2003.1252267
- Coccia, M. (2004). Spatial metrics of the technological transfer: Analysis and strategic management. *Technology Analysis & Strategic Management, 16*(1), 31-52. https://doi.org/10.1080/0953732032000175490
- Coccia, M. (2005). A Scientometric model for the assessment of scientific research performance within public institutes. *Scientometrics, 65*(3), 307-321. https://doi.org/10.1007/s11192-005-0276-1
- Coccia, M. (2005). Measuring intensity of technological change: The seismic approach. *Technological Forecasting & Social Change, 72*(2), 117-144. https://doi.org/10.1016/j.techfore.2004.01.004
- Coccia, M. (2005). Metrics to measure the technology transfer absorption: Analysis of the relationship between institutes and adopters in northern Italy. *International Journal of Technology Transfer and Commercialization, 4*(4), 462-486. https://doi.org/10.1504/IJTTC.2005.006699
- Coccia, M. (2006). Analysis and classification of public research institutes. *World Review of Science, Technology and Sustainable Development, 3*(1), 1-16. https://doi.org/10.1504/WRSTSD.2006.008759
- Coccia, M. (2008). New organizational behaviour of public research institutions: Lessons learned from Italian case study. *International Journal of Business Innovation and Research, 2*(4), 402–419. https://doi.org/10.1504/IJBIR.2008.018589
- Coccia, M. (2008). Spatial mobility of knowledge transfer and absorptive capacity: Analysis and measurement of the impact within the geoeconomic space. *The Journal of Technology Transfer, 33*(1), 105-122. https://doi.org/10.1007/s10961-007-9032-4
- Coccia, M. (2009). What is the optimal rate of R&D investment to maximize productivity growth? *Technological Forecasting & Social Change, 76*(3), 433-446. https://doi.org/10.1016/j.techfore.2008.02.008
- Coccia, M. (2010). Foresight of technological determinants and primary energy resources of future economic long waves. *International Journal of Foresight and Innovation Policy, 6*(4), 225–232. https://doi.org/10.1504/IJFIP.2010.037468
- Coccia, M. (2010). Public and private R&D investments as complementary inputs for productivity growth. *International Journal of Technology, Policy and Management, 10*(1/2), 73-91. https://doi.org/10.1504/IJTPM.2010.032855
- Coccia, M. (2010). Spatial patterns of technology transfer and measurement of its friction in the geo-economic space. *International Journal of Technology Transfer and Commercialisation, 9*(3), 255-267.

https://doi.org/10.1504/IJTTC.2010.030214

- Coccia, M. (2012). Converging genetics, genomics and nanotechnologies for groundbreaking pathways in biomedicine and nanomedicine. *International Journal of Healthcare Technology and Management, 13*(4), 184-197. https://doi.org/10.1504/IJHTM.2012.050616
- Coccia, M. (2012). Evolutionary trajectories of the nanotechnology research across worldwide economic players. *Technology Analysis & Strategic Management, 24*(10), 1029-1050. https://doi.org/10.1080/09537325.2012.705117
- Coccia, M. (2014). Converging scientific fields and new technological paradigms as main drivers of the division of scientific labour in drug discovery process: the effects on strategic management of the R&D corporate change. *Technology Analysis & Strategic Management, 26*(7), 733-749. https://doi.org/10.1080/09537325.2014.882501
- Coccia, M. (2014). Socio-cultural origins of the patterns of technological innovation: What is the likely interaction among religious culture, religious plurality and innovation? Towards a theory of socio-cultural drivers of the patterns of technological innovation. *Technology in Society, 36*(1), 13-25. https://doi.org/10.1016/j.techsoc.2013.11.002
- Coccia, M. (2015). General sources of general purpose technologies in complex societies: Theory of global leadership-driven innovation, warfare and human development. *Technology in Society, 42*, 199-226. https://doi.org/10.1016/j.techsoc.2015.05.008
- Coccia, M. (2015). Spatial relation between geo-climate zones and technological outputs to explain the evolution of technology. *International Journal of Transitions and Innovation Systems, 4*(1-2), 5-21. https://doi.org/10.1504/IJTIS.2015.074642
- Coccia, M. (2015). Technological paradigms and trajectories as determinants of the R&D corporate change in drug discovery industry. *International Journal of Knowledge and Learning, 10*(1), 29–43. https://doi.org/10.1504/IJKL.2015.071052
- Coccia, M. (2016). Radical innovations as drivers of breakthroughs: characteristics and properties of the management of technology leading to superior organizational performance in the discovery process of R&D labs. *Technology Analysis & Strategic Management, 28*(4), 381-395. https://doi.org/10.1080/09537325.2015.1095287
- Coccia, M. (2016). The relation between price setting in markets and asymmetries of systems of measurement of goods. *The Journal of Economic Asymmetries, 14*(Part B), 168-178. https://doi.org/10.1016/j.jeca.2016.06.001
- Coccia, M. (2017). Sources of disruptive technologies for industrial change. *L'industria – Rivista di Economia e Politica Industriale, 38*(1), 97-120. https://doi.org/10.1430/87140
- Coccia, M. (2017). Sources of technological innovation: Radical and incremental innovation problem-driven to support competitive advantage of firms. *Technology Analysis & Strategic Management, 29*(9), 1048-1061. https://doi.org/10.1080/09537325.2016.1268682
- Coccia, M. (2017). The Fishbone diagram to identify, systematize and analyze the sources of general purpose technologies. *Journal of Social and Administrative Sciences, 4*(4), 291-303. https://doi.org/10.1453/jsas.v4i4.1518
- Coccia, M. (2017). The source and nature of general purpose technologies for supporting next K-waves: Global leadership and the case study of the U.S. Navy's Mobile User Objective System. *Technological Forecasting & Social Change, 116*, 331-339. https://doi.org/10.1016/j.techfore.2016.05.019
- Coccia, M. (2017a). Disruptive firms and industrial change. *Journal of Economic and Social Thought, 4*(4), 437-450.

https://doi.org/10.1453/jest.v4i4.1511

- Coccia, M. (2017b). Varieties of capitalism's theory of innovation and a conceptual integration with leadership-oriented executives: the relation between typologies of executive, technological and socioeconomic performances. *International Journal of Public Sector Performance Management, 3*(2), 148-168. https://doi.org/10.1504/IJPSPM.2017.084672
- Coccia, M. (2018). A Theory of the General Causes of Long Waves: War, General Purpose Technologies, and Economic Change. *Technological Forecasting & Social Change, 128*, 287-295. https://doi.org/10.1016/j.techfore.2017.11.013
- Coccia, M. (2018). An introduction to the methods of inquiry in social sciences.*Journal of Administrative and Social Sciences (JSAS)*, 5(2), 116-126. https://doi.org/10.1453/jsas.v5i2.1651
- Coccia, M. (2018). Classification of innovation considering technological interaction.*Journal of Economics Bibliography*, 5(2), 76-93. https://doi.org/10.1453/jeb.v5i2.1650
- Coccia, M. (2018). Competition between basic and applied research in the organizational behaviour of public research labs. *Journal of Economics Library*, 5(2), 118-133. https://doi.org/10.1453/jel.v5i2.1652
- Coccia, M. (2018). Disruptive firms and technological change. *Quaderni IRCrES-CNR*, 3(1), 3-18. https://doi.org/10.23760/2499-6661.2018.001
- Coccia, M. (2018). General properties of the evolution of research fields: a scientometric study of human microbiome, evolutionary robotics and astrobiology. *Scientometrics*, 117(2), 1265-1283. https://doi.org/10.1007/s11192-018-2902-8
- Coccia, M. (2018). Optimization in R&D intensity and tax on corporate profits for supporting labor productivity of nations. *The Journal of Technology Transfer*, 43(3), 792-814. https://doi.org/10.1007/s10961-017-9572-1
- Coccia, M. (2018a). An introduction to the theories of institutional change.*Journal of Economics Library*, 5(4), 337-344. https://doi.org/10.1453/jel.v5i4.1788
- Coccia, M. (2018a). Theorem of not independence of any technological innovation.*Journal of Economics Bibliography*, 5(1), 29-35. https://doi.org/10.1453/jeb.v5i1.1578
- Coccia, M. (2019). A Theory of classification and evolution of technologies within a Generalized Darwinism.*Technology Analysis & Strategic Management*, 31(5), 517-531. https://doi.org/10.1080/09537325.2018.1523385
- Coccia, M. (2019). Artificial intelligence technology in oncology: a new technological paradigm.*arXiv.org e-Print archive*. Retrieved from http://arxiv.org/abs/1905.06871
- Coccia, M. (2019). Comparative Institutional Changes. In A. Farazmand (Ed.),*Global Encyclopedia of Public Administration, Public Policy, and Governance*. Springer. https://doi.org/10.1007/978-3-319-31816-5_1277-1
- Coccia, M. (2019). Comparative Theories of the Evolution of Technology. In A. Farazmand (Ed.),*Global Encyclopedia of Public Administration, Public Policy, and Governance*. Springer, Cham. https://doi.org/10.1007/978-3-319-31816-5_3841-1
- Coccia, M. (2019). Destructive technologies as driving forces of new technological cycles for industrial and corporate change. *Journal of Economic and Social Thought, 6*(4), 252-277. https://doi.org/10.1453/jest.v6i4.1973
- Coccia, M. (2019). Intrinsic and extrinsic incentives to support motivation and performance of public organizations. *Journal of Economics Bibliography, 6*(1), 20-29. https://doi.org/10.1453/jeb.v6i1.1795
- Coccia, M. (2019). *New Patterns of Technological Evolution: Theory and Practice*. KSP Books. ISBN: 978-605-7602-88-

6.

- Coccia, M. (2019). Technological Parasitism. *Journal of Economic and Social Thought, 6*(3), 173-209. https://doi.org/10.1453/jest.v6i3.1926
- Coccia, M. (2019). The theory of technological parasitism for the measurement of the evolution of technology and technological forecasting. *Technological Forecasting and Social Change, 141*, 289-304. https://doi.org/10.1016/j.techfore.2018.12.012
- Coccia, M. (2019). Theories of Revolution. In A. Farazmand (Ed.),*Global Encyclopedia of Public Administration, Public Policy, and Governance*. Springer, Cham. https://doi.org/10.1007/978-3-319-31816-5_3707-1
- Coccia, M. (2019). Theories of the evolution of technology based on processes of competitive substitution and multi-mode interaction between technologies. *Journal of Economics Bibliography, 6*(2), 99-109. https://doi.org/10.1453/jeb.v6i2.1889
- Coccia, M. (2019). What is technology and technology change? A new conception with systemic-purposeful perspective for technology analysis. *Journal of Social and Administrative Sciences, 6*(3), 145-169. https://doi.org/10.1453/jsas.v6i3.1957
- Coccia, M. (2019). Why do nations produce science advances and new technology?*Technology in Society, 59*, 101124, 1-9. https://doi.org/10.1016/j.techsoc.2019.03.007
- Coccia, M. (2019a). Killer Technologies: the destructive creation in the technical change.*arXiv.org e-Print archive, Cornell University, USA*. Retrieved from http://arxiv.org/abs/1907.12406
- Coccia, M. (2020). Asymmetry of the technological cycle of disruptive innovations.*Technology Analysis & Strategic Management, 32*(12), 1462-1477. https://doi.org/10.1080/09537325.2020.1785415
- Coccia, M. (2020). Comparative Concepts of Technology for Strategic Management. In A. Farazmand (Ed.),*Global Encyclopedia of Public Administration, Public Policy, and Governance*. Springer Nature. https://doi.org/10.1007/978-3-319-31816-5_3970-1
- Coccia, M. (2020). Deep learning technology for improving cancer care in society: New directions in cancer imaging driven by artificial intelligence. *Technology in Society, 60*, 101198, 1-11. https://doi.org/10.1016/j.techsoc.2019.101198
- Coccia, M. (2020). Destructive Technologies for Industrial and Corporate Change. In A. Farazmand (Ed.),*Global Encyclopedia of Public Administration, Public Policy, and Governance*. Springer, Cham. https://doi.org/10.1007/978-3-319-31816-5_3972-1
- Coccia, M. (2020). Fishbone diagram for technological analysis and foresight. *International Journal of Foresight and Innovation Policy, 14*(2/3/4), 225-247. https://doi.org/10.1504/IJFIP.2020.111221
- Coccia, M. (2020). The evolution of scientific disciplines in applied sciences: dynamics and empirical properties of experimental physics. *Scientometrics, 124*, 451-487. https://doi.org/10.1007/s11192-020-03464-y
- Coccia, M. (2020a). Deep learning technology for improving cancer care in society: New directions in cancer imaging driven by artificial intelligence. *Technology in Society, 60*, 101198, 1-11. https://doi.org/10.1016/j.techsoc.2019.101198
- Coccia, M. (2020b). Destructive Technologies for Industrial and Corporate Change. In A. Farazmand (Ed.),*Global Encyclopedia of Public Administration, Public Policy, and Governance*. Springer, Cham. https://doi.org/10.1007/978-3-319-31816-5_3972-1

- Coccia, M. (2020c). The evolution of scientific disciplines in applied sciences: dynamics and empirical properties of experimental physics. *Scientometrics, 124*, 451-487. https://doi.org/10.1007/s11192-020-03464-y
- Coccia, M. (2021). Effects of human progress driven by technological change on physical and mental health.*Studi di Sociologia, 2021*(2), 113-132. https://doi.org/10.26350/000309_000116
- Coccia, M. (2021). Technological Innovation. In G. Ritzer & C. Rojek (Eds.),*The Blackwell Encyclopedia of Sociology*. John Wiley & Sons, Ltd. https://doi.org/10.1002/9781405165518.wbeost011.pub2
- Coccia, M. (2022). Disruptive innovations in quantum technologies for social change.*Journal of Economics Bibliography, 9*(1), 21-39. https://doi.org/10.1453/jeb.v9i1.2287
- Coccia, M. (2022). Probability of discoveries between research fields to explain scientific and technological change. *Technology in Society, 68*, 101874. https://doi.org/10.1016/j.techsoc.2022.101874
- Coccia, M. (2022). Technological trajectories in quantum computing to design a quantum ecosystem for industrial change. *Technology Analysis & Strategic Management*. https://doi.org/10.1080/09537325.2022.2110056
- Coccia, M. (2023). High potential of technology to face new respiratory viruses: mechanical ventilation devices for effective healthcare to next pandemic emergencies. *Technology in Society, 73*, 102233. https://doi.org/10.1016/j.techsoc.2023.102233
- Coccia, M. (2023). Innovation Failure: Typologies for appropriate R&D management.*Journal of Social and Administrative Sciences, 10*(1-2), 10-30. https://doi.org/10.1453/jsas.v10i1-2.2435
- Coccia, M. (2023). New directions of technologies pointing the way to a sustainable global society.*Sustainable Futures, 5*, 100114. https://doi.org/10.1016/j.sftr.2023.100114
- Coccia, M. (2023). New perspectives in innovation failure analysis: A taxonomy of general errors and strategic management for reducing risks. *Technology in Society, 75*, 102384. https://doi.org/10.1016/j.techsoc.2023.102384
- Coccia, M. (2023). Promising technologies for fostering simultaneous environmental and socioeconomic sustainability. *Journal of Economic and Social Thought, 10*(1-2), 28-47. https://doi.org/10.1453/jest.v10i1-2.2452
- Coccia, M. (2018). Disruptive firms and technological change. *Quaderni IRCrES-CNR, 3*(1), 3-18. https://doi.org/10.23760/2499-6661.2018.001
- Coccia, M., & Bellitto, M. (2018). Human progress and its socioeconomic effects in society.*Journal of Economic and Social Thought, 5*(2), 160-178. https://doi.org/10.1453/jest.v5i2.1649
- Coccia, M., & Benati, I. (2018). Comparative models of inquiry. In A. Farazmand (Ed.),*Global Encyclopedia of Public Administration, Public Policy, and Governance*. https://doi.org/10.1007/978-3-319-31816-5_1199-1
- Coccia, M., & Benati, I. (2018). Comparative studies. In A. Farazmand (Ed.),*Global Encyclopedia of Public Administration, Public Policy, and Governance*, Bureaucracy (Chapter No. 1197-1, pp. 1-7). https://doi.org/10.1007/978-3-319-31816-5_1197-1
- Coccia, M., & Bontempi, E. (2023). New trajectories of technologies for the removal of pollutants and emerging contaminants in the environment. *Environmental Research, 229*, 115938. https://doi.org/10.1016/j.envres.2023.115938
- Coccia, M., Falavigna, G., & Manello, A. (2015). The impact of hybrid public and market-oriented financing mechanisms on scientific portfolio and performances of public research labs: A scientometric analysis. *Scientometrics, 102*(1), 151-168. https://doi.org/10.1007/s11192-014-1427-z

- Coccia, M., & Finardi, U. (2012). Emerging nanotechnological research for future pathway of biomedicine. *International Journal of Biomedical Nanoscience and Nanotechnology, 2*(3-4), 299-317. https://doi.org/10.1504/IJBNN.2012.051223
- Coccia, M., & Finardi, U. (2013). New technological trajectories of non-thermal plasma technology in medicine. *International Journal of Biomedical Engineering and Technology, 11*(4), 337-356. https://doi.org/10.1504/IJBET.2013.055665
- Coccia, M., Finardi, U., & Margon, D. (2012). Current trends in nanotechnology research across worldwide geo-economic players. *The Journal of Technology Transfer, 37*(5), 777-787. https://doi.org/10.1007/s10961-011-9219-6
- Coccia, M., Ghazinoori, S., & Roshani, S. (2023). Evolutionary Pathways of Ecosystem Literature in Organization and Management Studies. *Research Square*. https://doi.org/10.21203/rs.3.rs-2499460/v1
- Coccia, M., Mosleh, M., & Roshani, S. (2022). Evolution of quantum computing: Theoretical and innovation management implications for emerging quantum industry. *IEEE Transactions on Engineering Management*. https://doi.org/10.1109/TEM.2022.3175633
- Coccia, M., Mosleh, M., & Roshani, S. (2024). Evolution of Quantum Computing: Theoretical and Innovation Management Implications for Emerging Quantum Industry. *IEEE Transactions on Engineering Management, 71*, 2270-2280. https://doi.org/10.1109/TEM.2022.3175633
- Coccia, M., & Rolfo, S. (2000). Ricerca pubblica e trasferimento tecnologico: il caso della regione Piemonte. In S. Rolfo (Ed.), *Innovazione e piccole imprese in Piemonte* (pp. 236-256). FrancoAngeli Editore.
- Coccia, M., & Rolfo, S. (2008). Strategic change of public research units in their scientific activity. *Technovation, 28*(8), 485-494. https://doi.org/10.1016/j.technovation.2008.02.005
- Coccia, M., & Roshani, S. (2024). General laws of funding for scientific citations: how citations change in funded and unfunded research between basic and applied sciences. *Journal of Data and Information Science, 9*(1), 1–18. https://doi.org/10.2478/jdis-2024-0005
- Coccia, M., Roshani, S., & Mosleh, M. (2021). Scientific Developments and New Technological Trajectories in Sensor Research. *Sensors, 21*(23), 7803. https://doi.org/10.3390/s21237803
- Coccia, M., & Wang, L. (2015). Path-breaking directions of nanotechnology-based chemotherapy and molecular cancer therapy. *Technological Forecasting & Social Change, 94*, 155–169. https://doi.org/10.1016/j.techfore.2014.09.007
- Coccia, M., & Wang, L. (2016). Evolution and convergence of the patterns of international scientific collaboration. *Proceedings of the National Academy of Sciences of the United States of America, 113*(8), 2057-2061. https://doi.org/10.1073/pnas.1510820113
- Coccia, M., & Watts, J. (2020). A theory of the evolution of technology: technological parasitism and the implications for innovation management. *Journal of Engineering and Technology Management, 55*, 101552. https://doi.org/10.1016/j.jengtecman.2019.11.003
- Coccia, M. (2024). Variability in Research Topics Driving Different Technological Trajectories. *Preprints, 2024*, 2024020603. https://doi.org/10.20944/preprints202402.0603.v1
- Coccia, M., & Roshani, S. (2024). Research funding and citations in papers of Nobel Laureates in Physics, Chemistry and Medicine, 2019-2020. *Journal of Data and Information Science, 9*(2), 1–25. https://doi.org/10.2478/jdis-2024-0006
- Coccia, M., Roshani, S., & Mosleh, M. (2022). Evolution of Sensor Research for Clarifying the Dynamics and Properties

of Future Directions. *Sensors, 22*(23), 9419. https://doi.org/10.3390/s22239419

- Colombo, M. G., Franzoni, C., & Veugelers, R. (2015). Going radical: Producing and transferring disruptive innovation. *The Journal of Technology Transfer, 40*(4), 663–669.
- Crane, D. (1972). Invisible Colleges: Diffusion of Knowledge in Scientific Communities. Chicago: University of Chicago Press.
- Daehler, C. C. (2003). Performance comparisons of co-occurring native and alien invasive plants: Implications for conservation and restoration. *Annual Review of Ecology, Evolution, and Systematics, 34*, 183–211.
- Dawkins, R. (1983). Universal Darwinism. In D. S. Bendall (Ed.), Evolution from Molecules to Man (pp. 403–425). Cambridge: Cambridge University Press.
- de Visser, K. E., & Joyce, J. A. (2023). The evolving tumor microenvironment: From cancer initiation to metastatic outgrowth. *Cancer Cell, 41*(3), 374–403. https://doi.org/10.1016/j.ccell.2023.02.016
- Dell Technologies. (2023). Transformer (machine learning model). Retrieved December 2023, from https://infohub.delltechnologies.com/l/generative-ai-in-the-enterprise/transformer-models/
- Den Hartigh, E., Ortt, J. R., Van De Kaa, G., & Stolwijk, C. C. M. (2016). Platform control during battles for market dominance: The case of Apple versus IBM in the early personal computer industry. *Technovation, 48-49*, 4–12. https://www.scopus.com/record/display.uri?eid=2-s2.0-84959116307&origin=resultslist&sort=plf-f&src=s&sid=74a1a6807071bb4d36c8dd0aa6ff78f7&sot=b&sdt=b&s=%28TITLE-ABS-KEY%28%22leadership%22+AND+innovation%29+AND+TITLE-ABS-KEY%28apple%29%29&sl=43&sessionSearchId=74a1a6807071bb4d36c8dd0aa6ff78f7
- Denning, S. (2018). Succeeding in an increasingly Agile world. *Strategy and Leadership, 46*(3), 3–9.
- Devlin, J., Chang, M.-W., Lee, K., & Toutanova, K. (2018, October 11). BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding. *arXiv:1810.04805v2 [cs.CL]*. Retrieved from https://arxiv.org/abs/1810.04805v2
- Dosi, G. (1988). Sources, Procedures, and Microeconomic Effects of Innovation. *Journal of Economic Literature, 26*(3), 1120–1171. Retrieved from http://www.jstor.org/stable/2726526
- Duncan, R. (1976). The ambidextrous organization: Designing dual structures for innovation. In R. H. Killman, L. R. Pondy, & D. Sleven (Eds.), *The Management of Organization* (pp. 167-188). New York: North Holland.
- Essl, F., Dullinger, S., Rabitsch, W., Hulme, P. E., Hülber, K., Jarošík, V., Kleinbauer, I., Krausmann, F., Kühn, I., Nentwig, W., Vilà, M., Genovesi, P., Gherardi, F., Desprez-Loustau, M. L., Roques, A., & Pyšek, P. (2011). Socioeconomic legacy yields an invasion debt. *Proceedings of the National Academy of Sciences of the United States of America, 108*(1), 203–207. https://doi.org/10.1073/pnas.1011728108
- Etzkowitz, H., & Leydesdorff, L. (1998). A Triple Helix of University—Industry—Government Relations: Introduction. *Industry and Higher Education, 12*(4), 197-201. https://doi.org/10.1177/095042229801200402
- Farrell, C. J. (1993). A theory of technological progress. *Technological Forecasting and Social Change, 44*(2), 161-178.
- Fisher, J. C., & Pry, R. H. (1971). A Simple Substitution Model of Technological Change. *Technological Forecasting and Social Change, 3*, 75-88. https://doi.org/10.1016/S0040-1625(71)80005-7
- Fortunato, S., Bergstrom, C. T., Börner, K., Evans, J. A., Helbing, D., Milojević, S., Petersen, A. M., Sinatra, R., Uzzi,

B., Vespignani, A., Waltman, L., Wang, D., & Barabási, A. L. (2018). Science of science. *Science, 359*(6379), eaao0185. https://doi.org/10.1126/science.aao0185

- Foster, R. N. (1986). *Innovation: the attacker's advantage*. New York: Simon and Schuster.
- Freeman, C. (1974). *The economics of industrial innovation*. Harmondsworth: Penguin.
- Garud, R., Simpson, B., Langley, A., & Tsoukas, H. (Eds.). (2015). *The Emergence of Novelty in Organizations*. Oxford University Press.
- Gholizadeh, H., Rakotoarivony, M. N. A., Hassani, K., Johnson, K. G., Hamilton, R. G., Fuhlendorf, S. D., Schneider, F. D., & Bachelot, B. (2024). Advancing our understanding of plant diversity-biological invasion relationships using imaging spectroscopy. *Remote Sensing of Environment, 304*, 114028. https://doi.org/10.1016/j.rse.2024.114028
- Guimera, R., Uzzi, B., Spiro, J., & Amaral, L. (2008). Team assembly mechanisms determine collaboration network structure and team performance. *Science, 308*, 697–702.
- Henderson, R. (2006). The Innovator's Dilemma as a problem of organizational competence. *Journal of Product Innovation Management, 23*, 5–11.
- Hicks, D., & Isett, K. (2020). Powerful numbers: Exemplary quantitative studies of science that had policy impact. *Quantitative Studies of Science*. Retrieved from http://works.bepress.com/diana_hicks/54/
- Hill, C., & Rothaermel, F. (2003). The performance of incumbent firms in the face of radical technological innovation. *Academy of Management Review, 28*, 257–274.
- Hodgson, G. M. (2002). Darwinism in economics: From analogy to ontology. *Journal of Evolutionary Economics, 12*, 259–281.
- Hodgson, G. M., & Knudsen, T. (2006). Why we need a generalized Darwinism, and why generalized Darwinism is not enough. *Journal of Economic Behavior and Organization, 61*(1), 1–19.
- Hodgson, G. M., & Knudsen, T. (2008). In search of general evolutionary principles: Why Darwinism is too important to be left to the biologists. *Journal of Bioeconomics, 10*(1), 51–69.
- Hulme, P. E. (2012). Weed risk assessment: A way forward or a waste of time? *Journal of Applied Ecology, 49*, 10–19.
- Iacopini, I., Milojević, S., & Latora, V. (2018). Network dynamics of innovation processes. *Physical Review Letters, 120*(048301), 1-6. https://doi.org/10.1103/PhysRevLett.120.048301
- Jeschke, J. M., Aparicio, L. G., Haider, S., Heger, T., Lortie, C. J., Pyšek, P., & Strayer, D. L. (2012). Support for major hypotheses in invasion biology is uneven and declining. *NeoBiota, 20*, 1–20.
- Jovanovic, B., & Rousseau, P. L. (2005). General purpose technologies. In P. Aghion & S. N. Durlauf (Eds.), *Handbook of Economic Growth* (Vol. 1B, Ch. 18). Elsevier, Amsterdam.
- Kariampuzha, W., Alyea, G., Qu, S., Sanjak, J., Mathé, E., Sid, E., Chatelaine, H., Yadaw, A., Xu, Y., & Zhu, Q. (2023). Precision information extraction for rare disease epidemiology at scale. *Journal of Translational Medicine, 21*(1), 157. https://doi.org/10.1186/s12967-023-04011-y
- Kauffman, S. A. (2000). *Investigations*. Oxford University Press.
- Kauffman, S. A. (2016). *Humanity in a Creative Universe*. Oxford University Press.
- Kauffman, S. A. (2019). *A World Beyond Physics: The Emergence and Evolution of Life*. Oxford University Press.
- Kauffman, S. A., & Gare, A. (2015). Beyond Descartes and Newton: Recovering life and humanity. *Progress in*

Biophysics and Molecular Biology, 119(3), 219–244.

- Kauffman, S. A., & Clayton, P. (2006). On emergence, agency, and organization. *Biology and Philosophy, 21*(4), 501–521.
- Kauffman, S. A. (1996). Investigations: The nature of autonomous agents and the worlds they mutually create. *SFI Working Papers*. Santa Fe Institute.
- Kessler, E. H., & Chakrabarti, A. K. (1996). Innovation speed: A conceptual model of context, antecedents, and outcomes. *Academy of Management Review, 21*(4), 1143–1191.
- Krakhmal, N. V., Zavyalova, M. V., Denisov, E. V., Vtorushin, S. V., & Perelmuter, V. M. (2015). Cancer invasion: Patterns and mechanisms. *Acta Naturae, 7*(2), 17–28.
- Krinkin, K., Shichkina, Y., & Ignatyev, A. (2023). Co-evolutionary hybrid intelligence is a key concept for the world intellectualization. *Kybernetes, 52*(9), 2907–2923. https://doi.org/10.1108/K-03-2022-0472
- Kueffer, C. (2010). Transdisciplinary research is needed to predict plant invasions in an era of global change. *Trends in Ecology & Evolution, 25*, 619–620.
- Kueffer, C. (2012). The importance of collaborative learning and research among conservationists from different oceanic islands. *Revue d'Ecologie (Terre et Vie), 11*(Suppl.), 125–135.
- Kueffer, C., Pyšek, P., & Richardson, D. M. (2013). Integrative invasion science: model systems, multi-site studies, focused meta-analysis and invasion syndromes. *The New Phytologist, 200*(3), 615–633. https://doi.org/10.1111/nph.12415
- Lehman, N. E., & Kauffman, S. A. (2021). Constraint closure drove major transitions in the origins of life. *Entropy, 23*(1), 105. https://doi.org/10.3390/e23010105
- Levit, G. S., Hossfeld, U., & Witt, U. (2011). Can Darwinism be "generalized" and of what use would this be? *Journal of Evolutionary Economics, 21*(4), 545–562. https://doi.org/10.1007/s00191-011-0229-2
- Lipsey, R. G., Bekar, C. T., & Carlaw, K. I. (1998). What requires explanation? In E. Helpman (Ed.), *General Purpose Technologies and Long-term Economic Growth* (pp. 15–54). MIT Press.
- Lipsey, R. G., Carlaw, K. I., & Bekar, C. T. (2005). *Economic Transformations: General Purpose Technologies and Long Term Economic Growth* (pp. 131–218). Oxford University Press.
- Coccia, M. (2019). A theory of classification and evolution of technologies within a Generalised Darwinism. *Technology Analysis & Strategic Management, 31*(5), 517–531. https://doi.org/10.1080/09537325.2018.1523385
- Coccia, M. (2020). Asymmetry of the technological cycle of disruptive innovations. *Technology Analysis & Strategic Management, 32*(12), 1462–1477. https://doi.org/10.1080/09537325.2020.1785415
- Coccia, M. (2018). Classification of innovation considering technological interaction. *Journal of Economics Bibliography, 5*(2), 76–93. http://dx.doi.org/10.1453/jeb.v5i2.1650
- Coccia, M. (2019). Comparative institutional changes. In A. Farazmand (Ed.), *Global Encyclopedia of Public Administration, Public Policy, and Governance*. Springer International Publishing. https://doi.org/10.1007/978-3-319-31816-5_1277-1
- Coccia, M. (2020). Destructive technologies for industrial and corporate change. In A. Farazmand (Ed.), *Global Encyclopedia of Public Administration, Public Policy, and Governance*. Springer International Publishing.

https://doi.org/10.1007/978-3-319-31816-5_3972-1

- Coccia, M. (2023). New perspectives in innovation failure analysis: A taxonomy of general errors and strategic management for reducing risks. *Technology in Society, 75*, 102384. https://doi.org/10.1016/j.techsoc.2023.102384
- Coccia, M. (2012). Political economy of R&D to support the modern competitiveness of nations and determinants of economic optimization and inertia. *Technovation, 32*(6), 370–379. https://doi.org/10.1016/j.technovation.2012.03.005
- Coccia, M. (2016). Radical innovations as drivers of breakthroughs: characteristics and properties of the management of technology leading to superior organisational performance in the discovery process of R&D labs. *Technology Analysis & Strategic Management, 28*(4), 381–395. https://doi.org/10.1080/09537325.2015.1095287
- Coccia, M. (2017). Sources of technological innovation: Radical and incremental innovation problem-driven to support competitive advantage of firms. *Technology Analysis & Strategic Management, 29*(9), 1048–1061. https://doi.org/10.1080/09537325.2016.1268682
- Coccia, M. (2021). Technological Innovation. In G. Ritzer (Ed.), *The Blackwell Encyclopedia of Sociology* (1st ed., pp. 1–6). Wiley. https://doi.org/10.1002/9781405165518.wbeost011.pub2
- Coccia, M. (2022). Technological trajectories in quantum computing to design a quantum ecosystem for industrial change. *Technology Analysis & Strategic Management*, 1–16. https://doi.org/10.1080/09537325.2022.2110056
- Coccia, M. (2019). Why do nations produce science advances and new technology? *Technology in Society, 59*, 101124. https://doi.org/10.1016/j.techsoc.2019.03.007
- Coccia, M., Roshani, S., & Mosleh, M. (2022). Evolution of Quantum Computing: Theoretical and Innovation Management Implications for Emerging Quantum Industry. *IEEE Transactions on Engineering Management*, 1–11. https://doi.org/10.1109/TEM.2022.3175633
- Coccia, M., Roshani, S., & Mosleh, M. (2021). Scientific Developments and New Technological Trajectories in Sensor Research. *Sensors, 21*(23), 7803. https://doi.org/10.3390/s21237803
- March, J. G. (1991). Exploration and exploitation in organizational learning. *Organization Science, 2*, 71-87.
- Coccia, M. (2017a). Sources of disruptive technologies for industrial change. *L'industria*, (1), 97–120. https://doi.org/10.1430/87140
- Markides, C. (2006). Disruptive innovation: In need of better theory. *Journal of Product Innovation Management, 23*, 19-25.
- Mehdi, Y. (2023, February 7). Reinventing search with a new AI-powered Microsoft Bing and Edge, your copilot for the web. Microsoft. Retrieved February 2024, from https://blogs.microsoft.com/blog/2023/02/07/reinventing-search-with-a-new-ai-powered-microsoft-bing-and-edge-your-copilot-for-the-web/
- Menon, P. (2023). Introduction to Large Language Models and the Transformer Architecture. Medium. Retrieved February 19, 2024, from https://rpradeepmenon.medium.com/introduction-to-large-language-models-and-the-transformer-architecture-534408ed7e61
- Moles, A. T., Flores-Moreno, H., Bonser, S. P., Warton, D. I., Helm, A., Warman, L., Eldridge, D. J., Jurado, E., Hemmings, F. A., Reich, P. B., et al. (2012). Invasions: the trail behind, the path ahead, and a test of a disturbing idea. *Journal of Ecology, 100*, 116–127.
- Mosleh, M., Roshani, S., & Coccia, M. (2022). Scientific laws of research funding to support citations and diffusion of

knowledge in life science. *Scientometrics, 127*, 1931–1951. https://doi.org/10.1007/s11192-022-04300-1

- Nelson, R. R. (2008). Factors affecting the power of technological paradigms. *Industrial and Corporate Change, 17*(3), 485–497.
- Nelson, R. (2006). Evolutionary Social Science and Universal Darwinism. *Journal of Evolutionary Economics, 16*(5), 491–510.
- Norton, J. A., & Bass, F. M. (1987). A Diffusion Theory Model of Adoption and Substitution for Successive Generations of High-Technology Products. *Management Science, 33*(9), 1069–1086. http://www.jstor.org/stable/2631875
- Núñez-Delgado, A., Zhang, Z., Bontempi, E., Coccia, M., Race, M., & Zhou, Y. (2023). Editorial on the Topic "New Research on Detection and Removal of Emerging Pollutants." *Materials, 16*(2), 725. https://doi.org/10.3390/ma16020725
- OpenAI. (2015). Introducing OpenAI. Retrieved December 23, 2022, from https://web.archive.org/web/20170808104802/ https://openai.com/blog/introducing-openai/
- OpenAI. (2022). Introducing ChatGPT. Retrieved December 4, 2023, from https://openai.com/blog/chatgpt
- Oppenheimer, R. (1955). Analogy in Science. Paper presented at the Sixty-Third Annual Meeting of the American Psychological Association, San Francisco, CA.
- Pagliaro, M., & Coccia, M. (2021). How self-determination of scholars outclasses shrinking public research lab budgets, supporting scientific production: a case study and R&D management implications. *Heliyon, 7*(1), e05998. https://doi.org/10.1016/j.heliyon.2021.e05998
- Parker, J. D., Torchin, M. E., Hufbauer, R. A., Lemoine, N. P., Alba, C., Blumenthal, D. M., Bossdorf, O., Byers, J. E., Dunn, A. M., Heckman, R. W., et al. (2013). Do invasive species perform better in their new ranges? *Ecology, 98*, 985–994.
- Pelicice, F. M., Agostinho, A. A., Alves, C. B. M., et al. (2023). Unintended consequences of valuing the contributions of non-native species: misguided conservation initiatives in a megadiverse region. *Biodiversity and Conservation, 32*, 3915–3938. https://doi.org/10.1007/s10531-023-02666-z
- Pinaya, W. H. L., Graham, M. S., Kerfoot, E., Tudosiu, P.-D., Dafflon, J., Fernandez, V., Sanchez, P., Wolleb, J., da Costa, P. F., & Patel, A. (2023). Generative AI for Medical Imaging: extending the MONAI Framework. *arXiv:2307.15208*. https://arxiv.org/abs/2307.15208
- Porter, M. E. (1980). *Competitive strategy*. Free Press.
- Price, D. (1986). *Little science, big science*. Columbia University Press.
- Pyšek, P., Jarošík, V., Hulme, P. E., Pergl, J., Hejda, M., Schaffner, U., & Vilà, M. (2012). A global assessment of invasive plant impacts on resident species, communities and ecosystems: the interaction of impact measures, invading species' traits and environment. *Global Change Biology, 18*, 1725–1737.
- Pyšek, P., & Richardson, D. M. (2007). Traits associated with invasiveness in alien plants: where do we stand? In W. Nentwig (Ed.), *Biological invasions* (pp. 97–125). Heidelberg, Germany: Springer.
- Pyšek, P., Jarošík, V., Hulme, P. E., Kühn, I., Wild, J., Arianoutsou, M., Bacher, S., Chiron, F., Didziulis, V., Essl, F., et al. (2010). Disentangling the role of environmental and human pressures on biological invasions across Europe. *Proceedings of the National Academy of Sciences, USA, 107*, 12157–12162.

- Raisch, S., & Birkinshaw, J. (2008). Organizational ambidexterity: Antecedents, outcomes, and moderators.*Journal of Management, 34*, 375-409.
- Roco, M., & Bainbridge, W. (2002). Converging Technologies for Improving Human Performance: Integrating From the Nanoscale. *Journal of Nanoparticle Research, 4*, 281–295. https://doi.org/10.1023/A:1020128027306
- Rogers, E. M. (1962). *The Diffusion of Innovations*. New York: The Free Press.
- Rosenberg, N. (1976). *Perspectives on Technology*. New York: Cambridge University Press.
- Roshani, S., Coccia, M., & Mosleh, M. (2022). Sensor Technology for Opening New Pathways in Diagnosis and Therapeutics of Breast, Lung, Colorectal and Prostate Cancer. *HighTech and Innovation Journal, 3*(3), 356-375. https://doi.org/10.28991/HIJ-2022-03-03-010
- Roshani, S., Bagherylooieh, M. R., Mosleh, M., & Coccia, M. (2021). What is the relationship between research funding and citation-based performance? A comparative analysis between critical disciplines. *Scientometrics, 126*(9), 7859-7874. https://doi.org/10.1007/s11192-021-04077-9
- Sahal, D. (1981). *Patterns of Technological Innovation*. Reading, Massachusetts: Addison-Wesley Publishing Company, Inc.
- Schreiber, S. J., & Ryan, M. E. (2011). Invasion speeds for structured populations in fluctuating environments. *Theoretical Ecology, 4*, 423–434. https://doi.org/10.1007/s12080-010-0098-5
- Schubert, C. (2014). Generalized Darwinism and the Quest for an Evolutionary Theory of Policy-Making.*Journal of Evolutionary Economics, 24*(3), 479–513.
- Schuster, P. (2016). Major Transitions in Evolution and in Technology.*Complexity, 21*(4), 7–13. https://doi.org/10.1002/cplx.21773
- Scopus. (2024). Start exploring. Documents. Retrieved November 9, 2023, from https://www.scopus.com/search/form.uri?display=basic
- Smith, M. D., Knapp, A. K., & Collins, S. L. (2009). A framework for assessing ecosystem dynamics in response to chronic resource alterations induced by global change. *Ecology, 90*, 3279–3289.
- Stoelhorst, J. W. (2008). The Explanatory Logic and Ontological Commitments of Generalized Darwinism.*Journal of Economic Methodology, 15*(4), 343–363.
- Sun, X., Kaur, J., Milojevic, S., Flammini, A., & Menczer, F. (2013). Social Dynamics of Science.*Scientific Reports, 3*, 1069, 1-6. https://doi.org/10.1038/srep01069
- Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic Capabilities and Strategic Management.*Strategic Management Journal, 18*(7), 509–533. http://www.jstor.org/stable/3088148
- Eapen, T. T., Finkenstadt, D. J., Folk, J., & Venkataswamy, L. (2023). How Generative AI Can Augment Human Creativity. *Harvard Business Review*, June-August, 2023. https://hbr.org/2023/07/how-generative-ai-can-augment-human-creativity
- Tria, F., Loreto, V., Servedio, V. D. P., & Strogatz, S. H. (2014). The dynamics of correlated novelties.*Scientific Reports, 4*, 5890, 1-8. https://doi.org/10.1038/srep05890
- Tripsas, M. (1997). Unraveling the process of creative destruction: Complementary assets and incumbent survival in the typesetter industry. *Strategic Management Journal, 18*(Summer Special Issue), 119–142.

- Tushman, M., & Anderson, P. (1986). Technological Discontinuities and Organizational Environments. *Administrative Science Quarterly, 31*(3), 439–465.
- Tyagi, B. (2023). The Rise of Transformers: A Journey through Mathematics and Model Design in Neural Networks. *Medium*. https://tyagi-bhaumik.medium.com/the-rise-of-transformers-a-journey-through-mathematics-and-model-design-in-neural-networks-cdc599c58d12 (accessed February 2023)
- Utterback, J. M. (1994). Mastering the Dynamics of Innovation. Boston, MA: Harvard Business School Press.
- Utterback, J. M., & Brown, J. W. (1972). Monitoring for technological opportunities. *Business Horizons, 15*(October), 5–15.
- Utterback, J. M., Pistorius, C., & Yilmaz, E. (2019). The Dynamics of Competition and of the Diffusion of Innovations. MIT Sloan School Working Paper; 5519-18. http://hdl.handle.net/1721.1/117544
- Van Kleunen, M., Weber, E., & Fischer, M. (2010). A meta-analysis of trait differences between invasive and non-invasive plant species. *Ecology Letters, 13*, 235–245.
- Vaswani, A., Shazeer, N., Parmar, N., Uszkoreit, J., Jones, L., Gomez, A. N., Kaiser, L., & Polosukhin, I. (2017). Attention Is All You Need. *ArXiv* (Computation and Language and Machine Learning). https://arxiv.org/abs/1706.03762
- Wagner, A., & Rosen, W. (2014). Spaces of the possible: Universal Darwinism and the wall between technological and biological innovation. *Journal of the Royal Society, Interface, 11*(97), 20131190. https://doi.org/10.1098/rsif.2013.1190
- Wagner, C. (2008). *The new invisible college: Science for development*. Brookings Institution Press.
- Walker, L. R., & Smith, S. D. (1997). Impacts of invasive plants on community and ecosystem properties. In J. O. Luken & J. W. Thieret (Eds.), *Assessment and Management of Plant Invasions* (Springer Series on Environmental Management). Springer, New York, NY. https://doi.org/10.1007/978-1-4612-1926-2_7
- Wang, M.-H., & Kot, M. (2001). Speeds of invasion in a model with strong or weak Allee effects *Mathematical Biosciences, 171*(1), 83-97. https://doi.org/10.1016/S0025-5564(01)00048-7
- Wright, G. (1997). Towards a more historical approach to technological change. *The Economic Journal, 107*, 1560-1566.
- Ziman, J. (Ed.). (2000). *Technological innovation as an evolutionary process*. Cambridge University Press.