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Technological Convergence, Disruptive Innovation, and the Evolutionary Dynamics of Science and Technology in the Age of Artificial Intelligence and Quantum Systems

[1] Paolo Ricci
[1] Universidad de Buenos Aires, Argentina

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Abstract

The contemporary global economy is experiencing an unprecedented transformation driven by the accelerating convergence of scientific fields and technological paradigms. Artificial intelligence, quantum technologies, advanced sensor systems, nanotechnology, and biomedical innovations are no longer evolving in isolation but are increasingly intertwined through complex trajectories of co evolution, institutional interaction, and market driven adaptation. This article develops a comprehensive theoretical and empirical synthesis of how scientific knowledge and technological innovation evolve in this converging environment. Drawing strictly on the provided body of literature, this study integrates evolutionary theories of science, innovation management, and technological change with emerging evidence from artificial intelligence and quantum technology research. The objective is to articulate a unified framework that explains how disruptive and general purpose technologies emerge, spread, and reshape industries, research systems, and societies.

The article first situates technological change within long run evolutionary perspectives of science, building on Kuhnian paradigm shifts, Lakatosian research programmes, and modern scientometric models of scientific growth and collaboration. These theoretical foundations are then linked to Coccia's systemic purposeful conception of technology, which conceptualizes technological change as the outcome of cumulative, interactive, and goal oriented processes within complex socio economic systems. The dynamics of technological parasitism, technological convergence, and the rise of general purpose technologies are shown to provide an explanatory structure for understanding why certain technologies such as artificial intelligence and quantum computing achieve dominant roles in economic and scientific development.

Methodologically, this study adopts a qualitative comparative and evolutionary approach grounded in scientometric, bibliometric, and theoretical models developed in the science of science tradition. Instead of numerical modeling, the research reconstructs the pathways of technological evolution by synthesizing patterns observed across multiple research domains, including sensor technologies, cancer diagnostics, nanomedicine, artificial intelligence, and quantum computing. This approach allows for a detailed understanding of how funding structures, international collaboration networks, disruptive firms, and institutional frameworks jointly influence the direction and speed of technological progress.

Keywords: Technological convergence, disruptive innovation, artificial intelligence, quantum technologies, science evolution, innovation systems.

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1. Introduction

The evolution of science and technology has always been central to economic growth, social transformation, and the long term development of human civilization. From the industrial revolution to the digital age, waves of technological change have repeatedly reshaped production systems, labor markets, and geopolitical power structures. In the contemporary era, however, the pace, complexity, and interdependence of technological change have reached levels that demand new theoretical and analytical frameworks. Traditional linear models of innovation that assume a simple progression from basic science to applied technology and market diffusion are increasingly inadequate for capturing the multidimensional dynamics of modern innovation systems (Coccia, 2019; Fortunato et al., 2018).

At the heart of this transformation lies the phenomenon of technological convergence. Scientific disciplines and technological fields that were once distinct are now merging to create entirely new paradigms of knowledge and application. Genetics, nanotechnology, and information technologies converge in modern biomedicine and nanomedicine, reshaping diagnostic and therapeutic practices (Coccia, 2012; Coccia and Wang, 2015). Artificial intelligence integrates with sensor technologies to enable real time data driven decision making in healthcare, manufacturing, and urban management (Roshani et al., 2022; Coccia, 2019). Quantum computing, once a purely theoretical domain of physics, is rapidly evolving into an industrial technology with profound implications for cryptography, materials science, and optimization problems (Coccia and Roshani, 2024; Acin et al., 2018).

These converging trajectories raise fundamental questions about how science advances and how technologies emerge, diffuse, and transform societies. Kuhn’s theory of scientific revolutions emphasized the role of paradigm shifts in driving scientific progress, highlighting how normal science operates within established frameworks until anomalies accumulate and trigger revolutionary change (Kuhn, 1962). Lakatos further refined this view by proposing research programmes as evolving structures of theoretical and empirical commitments that compete for dominance (Lakatos et al., 1980). While these perspectives remain influential, the complexity of contemporary science requires integration with modern scientometric and network based approaches that examine how collaboration, funding, and institutional structures shape knowledge production (Price, 1986; Sun et al., 2013; Fortunato et al., 2018).

Coccia’s systemic purposeful conception of technology provides a powerful lens for integrating these perspectives. According to this framework, technology is not merely a collection of artifacts but a dynamic system of knowledge, skills, and organizational arrangements oriented toward specific socio economic goals (Coccia, 2019). Technological change is thus driven by purposeful efforts to solve problems, increase efficiency, and create new opportunities, but these efforts are constrained and enabled by broader institutional and scientific contexts. This view aligns with the observation that major technological breakthroughs often arise from the recombination of existing knowledge across different fields, rather than from isolated discoveries.

The contemporary landscape of artificial intelligence and quantum technologies exemplifies this systemic and convergent nature of innovation. Artificial intelligence draws on advances in computer science, statistics, cognitive science, and data engineering, while quantum technologies integrate physics, materials science, and information theory (Dhamija and Bag, 2020; Thew et al., 2019). These fields are also deeply embedded in global research networks and funding systems that shape their development trajectories (Coccia and Wang, 2016; Coccia and Roshani, 2024). As a result, understanding their evolution requires not only technical analysis but also a comprehensive theory of science and innovation.

Despite the richness of existing literature, significant gaps remain. Much research on technological change focuses on individual technologies or sectors, neglecting the broader patterns of convergence and co evolution that characterize modern innovation systems. Studies of disruptive innovation often emphasize market competition and firm level strategies, but they do not fully integrate the role of scientific research, funding regimes, and international collaboration in shaping technological trajectories (Christensen, 1997; Adner, 2002; Coccia, 2020). Similarly, scientometric analyses provide valuable insights into the growth and structure of research fields, yet they are rarely connected to theories of industrial change and technological parasitism.

This article addresses these gaps by developing an integrated framework that links the evolution of science, technological convergence, and disruptive innovation in the context of artificial intelligence and quantum technologies. By synthesizing the provided body of literature, the study aims to show how these domains co evolve through identifiable phases and how their interaction generates new opportunities and risks for nations, firms, and societies. The following sections elaborate this framework through a detailed methodological and theoretical analysis, followed by a comprehensive discussion of results and implications.

2. Methodology

The methodological approach of this study is grounded in the qualitative and theoretical traditions of the science of science and evolutionary innovation studies. Rather than relying on numerical models or statistical tests, the research adopts a comparative, interpretive, and synthetic methodology that draws on the rich conceptual and empirical insights provided by the referenced literature. This choice is justified by the nature of the research questions, which concern long term evolutionary processes, institutional dynamics, and the convergence of scientific and technological fields, phenomena that cannot be adequately captured through isolated quantitative indicators.

The primary methodological strategy involves a structured synthesis of multiple streams of literature, including theories of scientific change, models of technological evolution, and empirical studies of emerging technologies such as artificial intelligence, quantum computing, and sensor based biomedical systems. This synthesis is guided by Coccia's fishbone diagram approach to technological analysis, which emphasizes the identification and systematization of the multiple sources and drivers of general purpose technologies (Coccia, 2017; Coccia, 2020). By mapping how different scientific disciplines, technological capabilities, funding mechanisms, and institutional arrangements interact, the fishbone framework allows for a holistic understanding of technological trajectories.

In practice, this methodology involves several interrelated steps. First, the theoretical foundations of scientific and technological evolution are reconstructed by integrating classical perspectives from Kuhn, Lakatos, and Price with modern network and complexity based models of science dynamics (Kuhn, 1962; Lakatos et al., 1980; Price, 1986; Scharnhorst et al., 2012). This reconstruction provides a conceptual baseline for understanding how knowledge systems evolve over time.

Second, the study examines the concept of technological convergence and parasitism as developed by Coccia and collaborators. Technological parasitism describes the process by which new technologies draw on and exploit the capabilities of existing technologies, leading to asymmetric patterns of development and dependency (Coccia, 2019; Coccia and Watts, 2019). By analyzing how artificial intelligence and quantum technologies rely on and transform prior technological infrastructures, the study identifies key mechanisms of convergence and disruption.

Third, the methodology incorporates insights from scientometric and bibliometric studies of emerging technologies. Research on international collaboration networks, citation patterns, and funding effects provides empirical grounding for the theoretical claims about how science and technology co evolve (Coccia and Wang, 2016; Coccia and Roshani, 2024; Scheidsteger et al., 2021). These studies reveal how research fields grow, fragment, and converge, and how institutional factors shape these processes.

Fourth, the study integrates sector specific analyses of technologies in healthcare, sensor systems, and quantum computing. These domains are chosen because they exemplify the broader patterns of convergence and disruptive innovation under investigation. For example, the evolution of sensor technologies in cancer diagnosis illustrates how interdisciplinary research leads to new technological trajectories with significant social and economic impact (Roshani et al., 2022; Coccia et al., 2021).

Throughout this methodological process, the emphasis is on explanatory depth rather than empirical breadth. The goal is not to provide a comprehensive inventory of technologies or metrics, but to articulate a coherent narrative of how scientific knowledge and technological capabilities interact to produce transformative change. This approach is consistent with the evolutionary and systemic perspectives advocated in the referenced literature, which view innovation as an emergent property of complex adaptive systems rather than a linear outcome of isolated investments.

3. Results

The synthesis of theoretical and empirical literature reveals several robust patterns in the evolution of science and technology in the era of artificial intelligence and quantum systems. These patterns can be organized around three interrelated dimensions: the evolutionary phases of emerging technologies, the dynamics of technological convergence and parasitism, and the role of institutional and funding structures in shaping innovation trajectories.

One of the most significant findings is that emerging technologies such as artificial intelligence and quantum computing follow identifiable evolutionary phases that mirror, but also accelerate, the patterns observed in earlier general purpose technologies. According to Coccia and Roshani, emerging technologies typically begin with a phase of exploratory scientific research, characterized by high uncertainty, fragmented knowledge, and a focus on fundamental principles (Coccia and Roshani, 2024). In artificial intelligence, this phase was marked by early work on symbolic reasoning and neural networks, while in quantum technologies it involved theoretical studies of quantum information and computation (Acin et al., 2018; Thew et al., 2019).

This exploratory phase is followed by a period of consolidation, during which research programs coalesce around dominant paradigms and technological standards. In artificial intelligence, the rise of machine learning and deep learning provided such a unifying framework, enabling rapid progress across diverse application areas (Coccia, 2019; Dhamija and Bag, 2020). In quantum computing, the development of superconducting qubits and other hardware platforms has similarly focused research and investment (Arute et al., 2019).

The final phase involves the translation of scientific and technological capabilities into industrial and societal applications. This phase is characterized by the entry of disruptive firms, the formation of innovation ecosystems, and the restructuring of existing industries (Coccia, 2017; Christensen, 1997). Artificial intelligence is already well into this phase, with widespread adoption in healthcare, finance, and manufacturing, while quantum technologies are beginning to attract significant industrial interest.

A second major result concerns the dynamics of technological convergence and parasitism. The literature shows that new technologies rarely emerge in isolation; instead, they build on and exploit the capabilities of existing technologies, often in ways that create asymmetric dependencies. Coccia's theory of technological parasitism explains how dominant technologies can draw resources, knowledge, and market opportunities from older technologies, reshaping entire technological ecosystems (Coccia, 2019; Coccia and Watts, 2019). Artificial intelligence, for example, depends on advances in computing hardware, data storage, and sensor technologies, yet it also transforms these domains by redefining their value and applications.

Quantum technologies exhibit similar parasitic and convergent dynamics. They rely on classical computing for control and error correction, while also promising to disrupt cryptography, optimization, and simulation in ways that could undermine existing technological regimes (Coccia, 2022; Coccia, 2022). The result is a complex interplay of competition and complementarity that shapes the evolution of entire industries.

The third key finding relates to the role of institutional and funding structures in shaping these evolutionary trajectories. Studies of research funding and citation patterns demonstrate that funded research tends to receive more attention and to drive the development of applied technologies, while unfunded or underfunded research remains more confined to basic science (Coccia and Roshani, 2024). International collaboration networks further amplify these effects by enabling the rapid diffusion of knowledge and the concentration of expertise in leading research hubs (Coccia and Wang, 2016).

In the context of artificial intelligence and quantum technologies, these institutional dynamics have led to significant geographical and organizational asymmetries. A small number of nations and firms have emerged as global leaders, while others become dependent on imported technologies and expertise. This pattern reflects broader trends of technological parasitism and industrial change, in which disruptive firms and countries capture disproportionate value from innovation (Coccia, 2017; Coccia, 2020).

4. Discussion

The results of this study have profound implications for our understanding of how science and technology evolve in the contemporary world. By integrating theories of scientific change with models of technological convergence and disruptive innovation, the analysis provides a comprehensive framework for interpreting the complex dynamics of artificial intelligence and quantum technologies.

One of the most important theoretical implications is the recognition that technological change is fundamentally systemic and evolutionary. Rather than viewing innovation as a sequence of isolated breakthroughs, the evidence supports a view of innovation as the outcome of continuous interactions among scientific disciplines, technological capabilities, and institutional arrangements (Coccia, 2019; Fortunato et al., 2018). This perspective aligns with Kuhn's emphasis on paradigms and Lakatos's research programmes, but it extends these ideas by incorporating the role of networks, funding, and industrial actors.

The concept of technological parasitism adds an additional layer of explanatory power. By highlighting how new technologies exploit and transform existing ones, this theory explains why technological change often leads to both creative and destructive outcomes (Coccia, 2019; Calvano, 2007). In the case of artificial intelligence, for example, the automation of cognitive tasks creates new opportunities for efficiency and innovation, but it also threatens established professions and industries. Quantum technologies may similarly disrupt cryptography and cybersecurity, creating both risks and opportunities for social and economic systems.

From a policy and management perspective, these findings underscore the importance of investing in foundational science, interdisciplinary research, and international collaboration. Nations that focus narrowly on short term technological applications risk falling behind in the long run, as they become dependent on technologies developed elsewhere (Coccia, 2019; Wagner, 2008). Similarly, firms that fail to engage with emerging scientific paradigms may be overtaken by disruptive competitors that better integrate new knowledge into their innovation strategies (Christensen et al., 2015; Coccia, 2017).

The study also highlights the limitations of existing innovation policies that do not account for the convergent and parasitic nature of modern technologies. Traditional sector based approaches to research funding and industrial policy may be ill suited to managing technologies that span multiple domains and evolve through complex networks of interaction. More flexible and systemic approaches are needed to support the development of innovation ecosystems that can adapt to rapid technological change.

Despite its contributions, the study also has limitations. The reliance on qualitative synthesis means that the findings are interpretive rather than predictive. Future research could complement this approach with more detailed scientometric and network analyses to quantify the dynamics of convergence and parasitism in specific technological domains (Scheidsteger et al., 2021; Noyons and van Raan, 1998). Additionally, empirical studies of firm level and national level strategies could provide further insight into how different actors navigate these complex innovation landscapes.

5. Conclusion

The evolution of science and technology in the age of artificial intelligence and quantum systems is characterized by unprecedented levels of convergence, complexity, and disruption. By synthesizing theories of scientific change, technological parasitism, and innovation management, this article has provided a comprehensive framework for understanding these dynamics. The analysis demonstrates that emerging technologies follow identifiable evolutionary phases, are shaped by convergent and parasitic interactions, and are deeply influenced by institutional and funding structures.

Artificial intelligence and quantum technologies exemplify these patterns, offering both transformative opportunities and significant challenges for societies around the world. Their development will depend not only on technical breakthroughs but also on the ability of nations, firms, and research institutions to navigate the complex ecosystems of modern innovation. By adopting systemic and evolutionary perspectives, policymakers and managers can better anticipate the trajectories of emerging technologies and design strategies that promote sustainable and inclusive technological progress.

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