QUANTUM-SINGULAR ORIENTATION OF THE NEOTECHNOLOGY PARADIGM OF WORLD ECONOMIC DEVELOPMENT

Oleksiy Stupnytskyy[1]
Volodymyr Vergun[2]
Serhiy Borysov[3]

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Abstract. The chapter examines the quantum-singular orientation of the neotechnology paradigm of global economic development under conditions of accelerated digitalization, artificial intelligence (AI) diffusion, and the emergence of autonomous algorithmic systems. The study focuses on the transformation of the international economy from a human-centered model toward an algorithmically governed system characterized by nonlinear dynamics, self-learning technologies, and AI-to-AI interaction. Particular attention is devoted to the conceptualization of economic singularity as a new stage of global economic evolution associated with exponential and super-exponential growth driven by autonomous technological systems. The subject of the research is the transformation of the global economy under conditions of AI-driven singularity and the emergence of autonomous economic agents capable of independent decision-making, adaptation, and self-optimization. The purpose of the study is to identify the mechanisms, drivers, and structural consequences of singularity transformations in the international economy, as well as to substantiate the formation of a new logic of economic development based on algorithmic governance, endogenous technological growth, and complex adaptive systems.

[1] PhD in Economics, Professor,
Department of International Business, Institute of International Relations
at Taras Shevchenko National University of Kyiv, Ukraine
[2] Doctor of Economics, Professor,
Department of International Business,
Institute of International Relations
at Taras Shevchenko National University of Kyiv, Ukraine
[3] Assistant, Department of International Business,
Institute of International Relations
at Taras Shevchenko National University of Kyiv, Ukraine

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The methodological basis of the study combines the provisions of endogenous economic growth theory, complexity economics, theories of increasing returns, network interaction models, and concepts of technological singularity. The research applies interdisciplinary, systemic, comparative, and evolutionary approaches, as well as elements of formalized modeling and conceptual forecasting. The proposed Economic Singularity Framework (ESF) model explains the transition from the digital economy to the AI economy, autonomous economy, and economic singularity through the interaction of technological innovations, artificial intelligence, quantum computing, data intensity, and institutional adaptation. The study demonstrates that AI technologies increasingly perform not only auxiliary analytical functions but also strategic economic functions, gradually transforming into independent market participants. Autonomous AI agents are capable of generating knowledge, optimizing economic decisions, coordinating transactions, and interacting with other algorithmic systems without direct human intervention. This creates the prerequisites for the emergence of an AI-to-AI economy in which economic coordination is based on the speed of algorithmic interaction, machine learning efficiency, and access to data resources. The research substantiates that economic singularity should be interpreted as a systemic phase transition of the global economy characterized by the replacement of linear development trajectories with nonlinear self-reinforcing dynamics. Special attention is devoted to the phenomenon of super-exponential growth resulting from the interaction between AI, informational capital, energy singularity, bioeconomic singularity, and cognitive singularity. The chapter proves that increasing returns generated by non-rival informational goods and autonomous innovation systems may fundamentally alter the structure of production, labor markets, global competition, and international economic relations. The conclusions emphasize that the transition toward economic singularity represents not merely a technological modernization of the world economy but a transformation of the very principles of economic coordination, governance, and value creation. The future architecture of the international economy will increasingly depend on the interaction between autonomous AI systems, institutional adaptability, and the ability of states and international organizations to regulate emerging forms of algorithmic power and global technological asymmetries.

INTRODUCTION

The beginning of the twenty-first century has been marked by the rapid expansion of digital technologies, AI, quantum computing, platform business models, and autonomous algorithmic systems, which are fundamentally transforming the architecture of the global economy and international economic relations. Contemporary economic development is increasingly characterized not only by digitalization and automation but also by the gradual emergence of self-learning technological ecosystems capable of autonomous coordination, adaptation, and decision-making. Under such conditions, traditional economic theories based on linear development trajectories and human-centered governance are becoming insufficient for explaining the growing complexity, nonlinearity, and self-reinforcing nature of modern economic processes. The scientific novelty of the study lies in the conceptualization of economic singularity as a systemic phase transition of the global economy associated with the autonomization of economic decision-making, the emergence of AI-to-AI interaction, and the transformation of artificial intelligence from an auxiliary technological instrument into an independent economic agent. Unlike conventional approaches focused primarily on digitalization or platformization, this research proposes an interdisciplinary framework integrating endogenous growth theory, complexity economics, network interaction theory, and concepts of technological singularity in order to explain the transition from the digital economy toward an autonomous algorithmic economy.

The relevance of the research is determined by several interrelated factors. First, the global diffusion of AI technologies and autonomous systems is radically changing the mechanisms of production, finance, logistics, governance, and international competition. Second, the accelerated growth of informational capital and the increasing role of data as a strategic economic resource create fundamentally new forms of market coordination and competitive advantage. Third, the emergence of algorithmically governed ecosystems and platform monopolies intensifies global technological asymmetries and transforms the balance of economic power within the world economy. Finally, the growing possibility of super-exponential economic growth generated by self-learning AI systems raises new theoretical and practical questions regarding institutional adaptation, labor market restructuring, international regulation, and economic security.

The research relies on the provisions of endogenous economic growth theory, theories of increasing returns, complexity economics, complex adaptive systems theory, and futurological approaches to technological singularity. Methods of comparative analysis, structural-functional analysis, logical generalization, conceptual modeling, and formalized analytical interpretation are employed. The chapter also incorporates elements of agent-based reasoning and nonlinear dynamic analysis to explain the interaction between autonomous algorithmic systems and global economic structures.

The logic of the chapter is organized according to the gradual transition from theoretical foundations toward systemic interpretation of singularity transformations. The first section examines the evolution of the concepts of technological and economic singularity and substantiates the formation of the Economic Singularity Framework. The second section analyzes the transformation of the international economy under conditions of AI autonomy and the emergence of AI-to-AI interaction as a new mechanism of economic coordination. The third section investigates the phenomenon of super-exponential growth and explores the interconnection between economic, energy, bioeconomic, and cognitive singularities within the emerging neotechnology paradigm of global development. Thus, the chapter seeks to provide a comprehensive theoretical explanation of how the convergence of AI technologies, informational capital, autonomous systems, and nonlinear economic dynamics is reshaping the modern world economy and creating the preconditions for a qualitatively new stage of global economic evolution.

1. From Digitalization to Singularity: A New Logic of Global Development in the Context of the AI Economy

The current stage of global economic development is characterized by profound transformational processes driven by digitalization, globalization, and the rapid advancement of AI technologies. The implementation of intelligent systems in various spheres of economic activity not only changes management tools but also gradually transforms the very nature of economic relations. Under these conditions, traditional theoretical approaches are increasingly proving insufficient to explain new phenomena associated with the growing autonomy of technological systems. In particular, increasing

importance is being attached to the processes of delegating economic decision-making to algorithmic systems, which create opportunities for the emergence of autonomous agents capable of independent interaction and adaptation.

Of particular relevance is the issue of understanding qualitative changes in the functioning of the economy that go beyond gradual evolution and acquire the characteristics of leap-like development. Such processes are increasingly interpreted through the prism of the concepts of technological and economic singularities, which imply the achievement of a critical point after which the pace of change becomes uncontrollable and the further development of the system becomes difficult to predict. At the same time, the development of the digital economy, the spread of platform business models, and the growing role of algorithmic governance indicate the formation of a new logic of market functioning based on the achievements of endogenous economic growth theory and complex systems theory, which provide the methodological foundation for analyzing nonlinear and self-reinforcing processes in the economy.

In 1958, the Hungarian-American mathematician and physicist J. von Neumann first used the concept of "singularity" directly in a technological context, although it had long existed as a mathematical abstraction [1]. In 1965, G. Moore observed that the number of transistors on an integrated circuit doubled approximately every 24 months, implying that computers were becoming more powerful, their cost per unit of performance was decreasing, and technological progress was accelerating. In other words, there existed a qualitative progression that could be empirically observed and represented graphically as an exponential curve. Since many other similar progressions exist as consequences of more fundamental, general, and global processes, this phenomenon became known as "*Moore's Law*" [2].

In 1963, the British-American historian of science D. Price formulated the "Law of Exponential Growth of Knowledge," which became the foundation of scientometrics and influenced the ideas of technological singularity [3]. D. Price discovered that the number of scientific journals and publications doubled approximately every 10–15 years; thus, the volume of scientific knowledge (the number of articles, books, and discoveries) grows not linearly but exponentially. Knowledge doubles over specific intervals of

time, and each new generation of scientists creates more information than the previous one. Therefore, the growth of existing knowledge accelerates the emergence of new knowledge. He also empirically demonstrated that exponential growth cannot continue indefinitely, as it inevitably encounters limitations such as resources, attention, and funding, after which a transition to another growth model becomes possible, involving either slowdown or "saturation."

In their studies of singularity, V. Vinge [4] and R. Kurzweil [5] attempted to understand the moment when technological development, particularly AI, would become so rapid and radical that humanity would no longer be able to predict or control it in the usual way. V. Vinge introduced the concept of a "point of unpredictability": singularity is an unpredictable "moment after which the rules of the game change completely," occurring when superintelligence emerges through the creation of AI, the enhancement of the human brain (cyborgization), and the networking of intelligences. In turn, R. Kurzweil developed the theory of "exponential development," proving that technologies evolve according to the principle of nonlinear exponential growth, especially evident in computing technology through Moore's Law. According to his forecast, singularity as an evolutionary leap will occur approximately in the middle of the twenty-first century. Thus, while V. Vinge emphasizes uncertainty and risk, R. Kurzweil focuses on technological progress and opportunities. Nevertheless, the common essence of their research lies in the idea that technological development leads to the emergence of intelligence more powerful than human intelligence, changing human nature itself, and that this moment will become a turning point for civilization, transforming the economy as well.

Therefore, according to the generally accepted definition, *economic singularity* is a specific hypothetical state of economic development in which AI and other technologies become so advanced that humanity undergoes dramatic and irreversible changes, while the economy itself transforms from a "human-centered" system into an algorithmically governed one. As for classical economic theory, this category has not yet become a fully explored concept within economics, as it is borrowed from the logic of technological singularity. However, at present, several *main characteristics* of economic singularity can be identified. First, the pace of technological progress is increasingly acquiring exponential, primarily in the sphere of

AI and automation, and uncontrollable forms. Second, traditional economic laws such as supply and demand or labor and capital are losing their classical explanatory power. Third, key decisions are increasingly shifting from human workers to intelligent systems (AI, Quantum AI).

The accelerated dynamics of modern technological trends determine the speed and complexity of the economy under conditions where the processes of technological transformation themselves exceed human understanding. Workers are transformed from the "center of decision-making" into the periphery of the process. In other words, key economic decisions are made not by humans but by interacting algorithms. This is no longer merely about automation but about a full-fledged economic ecosystem in which AI functions as an agent or network of agents, while companies as algorithmic structures conduct commercial activity on the basis of smart contracts in conditions where markets acquire the form of self-regulating platforms. This is perceived as more radical than simple digitalization or globalization because the self-acceleration of the system – economic singularity – is determined by corresponding algorithms that optimize one another and lead to exponential development, creating the effect of an "economy that improves itself." The significance of new forms of competition is growing: it is no longer countries that compete, but ecosystems of data and algorithmic architectures based on the speed of learning new management models.

Under conditions of radical transformation in the mechanisms of value creation, the structure of the labor market, and the principles of economic decision-making, economic singularity implies not merely a fundamentally new stage of economic development but a change in the very logic of its functioning. Algorithmic trading in financial markets, AI-driven solutions in logistics and energy, and corporate ecosystems/platforms such as Amazon or Google, where decisions are made on the basis of data, lead, on the one hand, to a sharp increase in economic efficiency, reductions in the cost of goods and services, and the acceleration of technological breakthroughs. On the other hand, they lead to technological inequality among countries in the world economy, the concentration of economic power within the emerging "core" of international Big Tech corporations, and the loss of control over national and global economic processes.

The *key features* of economic singularity include:

– exponential productivity growth (automation leads to minimal marginal costs, and production becomes almost "free");

– the dominance of AI in decision-making practices (transforming financial markets into systems of algorithms, logistics into autonomous systems, and governance into data-driven governance);

– transformation of the labor market (mass displacement of routine labor, growing importance of creative and strategic professions, and the emergence of concepts such as Universal Basic Income);

– changes in the nature of value (data and algorithms become the main resource, while traditional factors such as land and labor lose their dominant role);

– instability and nonlinearity (markets become less predictable as classical market models cease to function effectively).

Regarding the conceptual formalized model of the *Economic Singularity Framework* (ESF), the economic system passes through the following successive stages of transformation under the influence of technology: *"classical economy → digital economy → AI economy → autonomous economy → economic singularity."* It is necessary to clearly distinguish between the levels and stages of development within the ESF model.

At Level 1, the technological core (AI, Quantum Computing, Big Data, and automation) generates exponential growth. Level 2 (digital platforms, cloud computing, quantum networks, and IoT) ensures scalability. Level 3 is associated with the functioning of economic processes (production, finance, logistics, and energy), which transition into a data-driven mode. The adaptive institutional system (the state, markets, regulators, and corporations), together with the resulting outcomes (a new economic reality, algorithmic governance, and economic singularity), determine Levels 4 and 5 of the ESF model. In essence, this is a "model of transition from an economy of human decisions to an economy of algorithmic decisions."

Under conditions of accelerated innovation development and the decreasing role of human labor, a system transitioning into a state of singularity may be represented as a functional dependence of key elements with corresponding time intervals/lags:

$$ES(t) = f(TI, AI, QC, DATA, INST),$$

where:

– *ES* – the level of "singularity";

– *TI* – technological innovations;
– *AI* – artificial intelligence;
– *QC* – quantum computing;
– *DATA* – the volume and quality of data;
– *INST* – institutional adaptation.

The stages of development (*Stage Model ESF*) are formed according to the following scale (Table 1).

Table 1

Stages of Development of the Economic Singularity Framework Model

Stage	Characteristics	Result
Stage 1: Digital Foundation	digitalization of the economy, development of platforms	transition to a data-driven economy
Stage 2: AI Augmentation	AI assists in decision-making, process automation	increased efficiency
Stage 3: Autonomous Systems	systems operate autonomously with minimal human involvement	algorithmic markets
Stage 4: Self-Optimizing Economy	the economy becomes self-learning with continuous optimization	nonlinear dynamics
Stage 5: Economic Singularity	exponential speed of change, loss of classical models	a new economic paradigm

Source: compiled by the authors

Thus, the ESF reflects the transition from a linear, human-controlled economy to a nonlinear, self-regulating system in which technologies become the leading subject of economic dynamics. In this context, the main KPIs in the process of transition toward singularity should include: the level of automation (percentage of processes without human participation), the share of AI-based decisions (percentage in managerial decision-making), the speed of innovation (*time-to-market*), dependence on data (*data intensity*), and system flexibility (*adaptability*). At the same time, the key drivers of the model (accelerators) are the development of AI, quantum technologies, and global crises as catalysts, against the background of growing regulatory barriers, ethical issues, and limited energy resources.

At present, the foundation of the *mechanism of economic singularity* is the ability of AI systems to engage in self-learning, which ensures the endogenization of technological progress. Unlike classical models, in which innovations are considered an external factor, in this case development becomes an intrinsic property of the system itself. Its key element is not merely the formation and dissemination of AI, but the emergence of a self-accelerating system of autonomous agents capable of continuous improvement and interaction without direct human intervention or control.

In this context, economic singularity is regarded, on the one hand, as a qualitative transition of the system into a state where the speed, complexity, and autonomy of economic processes exceed the capabilities of their traditional (human-centered) governance. On the other hand, it is viewed as a qualitative leap in the development of the global economy that exhibits the characteristics of a nonlinear dynamic system and corresponds to the logic of modern research in the field of complex systems theory.

The functions of the autonomous agents within this mechanism include the accumulation of data during operation, the adaptation of their own algorithms through machine learning mechanisms, and the optimization not only of decisions themselves but also of the decision-making models. In such a system, each new cycle increases the efficiency of the previous one, which, first, creates the preconditions for nonlinear development and forms a closed improvement cycle: "*data → learning → decisions → new data → improved learning*." Second, it determines the nature of AI-to-AI interaction as a new level of economic coordination associated with the transition from the "human–AI" model to the network interaction of autonomous AI agents.

At the same time, agents not only exchange data and signals in real time and conclude transactions (through digital platforms or smart contracts), but also – and most importantly – coordinate behavior within this configuration without centralized governance. As a result, a specific distributive system of economic coordination emerges, characterized by high-speed agreement of decisions, minimization of information asymmetries, and adaptability to changes in both the internal and external environment. It is fundamentally important that the efficiency of each individual AI agent increases with the growth in the number of other agents within the system, creating a second-order network effect in which the value of the system is determined not only

by the number of participants but also by the intensity of their algorithmic interaction.

An important outcome of the mechanism of economic singularity is the combination of self-learning and AI-to-AI interaction, which generates the *effect of exponential acceleration* in the development of the economic system. From a theoretical perspective, the effect of exponential acceleration may be explained through the concepts of positive feedback, increasing returns, and the nonlinear dynamics of economic processes. In this context, it is appropriate to refer to the ideas of B. Arthur [6; 7], who argued that processes of self-reinforcement dominate within technological economies and that equilibrium is not stable. In fact, the AI economy radicalizes this logic: a) each improvement of an algorithm strengthens future improvements; b) the system shifts into a regime of cumulative growth; c) even minor changes may produce disproportionately large consequences.

Thus, the logic of exponential acceleration lies in the continuity of the following process: "improved algorithms generate more efficient decisions, which create more data, while larger volumes of data accelerate learning, leading to even more advanced algorithms." This corresponds to the model of nonlinear systems with positive feedback, in which the trajectory of development is determined not only by initial conditions but also by internal mechanisms of self-reinforcement.

Consequently, the system transitions from linear dynamics to an exponential trajectory of development, where each subsequent stage qualitatively surpasses the previous one in terms of speed and complexity.

To generalize the functioning of the proposed mechanism, it is advisable to present it in the form of a simplified (formalized) analytical-conceptual model under conditions where, for example:

– At – the level of development of autonomous agents at time t;
– Dt – the volume of available data;
– It – the intensity of interaction between agents;
– Et – the efficiency of the economic system.

Under these conditions, the dynamics of the system may be described by the following relationships:

1. Self-learning: $At+1 = At + \alpha \cdot Dt \cdot At$
2. Data generation: $Dt+1 = Dt + \beta \cdot Et$
3. AI-to-AI interaction: $It = \gamma \cdot At2$

4. System efficiency: $Et = f(At, It)$

where $\alpha, \beta, \gamma > 0$ are sensitivity coefficients.

In the context of interpreting the model, three main conditions should be emphasized: a) the growth of At has a self-reinforcing character (an endogenous growth model); b) the interaction It grows quadratically, reflecting the network effect (a network interaction model); c) the efficiency of the system becomes a function not only of the level of development of agents but also of their interaction (a nonlinear dynamic system due to the interdependence of variables). This corresponds to approaches used in contemporary studies of agent-based modeling, complexity economics, and self-organization theory.

It is also critically important that there exists a threshold value A, after reaching which the system enters a regime of uncontrolled acceleration: $At > A \rightarrow$ the pace of system development exceeds the possibilities of its external regulation. According to the theory of phase transitions, this moment may be interpreted as the critical point of economic singularity at which the system changes its mode of functioning. Pre-threshold conditions (system controllability, gradual change, dominance of human control) are replaced by post-threshold conditions – self-organized dynamics emerge, the speed of change becomes uncontrollable, and macro-level properties can no longer be reduced solely to the intentions of individual agents or actors. Thus, singularity is not merely a technological phenomenon but a *systemic phase transition* of the modern global economy.

Therefore, the mechanism of economic singularity is based on the interaction of three interrelated approaches: the endogenization of innovation processes and the self-learning of autonomous agents (endogenous growth theory); the network self-organization of agents and their network interaction (complex adaptive systems theory); and nonlinear dynamics with positive feedback and exponential acceleration of development (the economics of increasing returns).

The synthesis of these approaches makes it possible to consider the contemporary transformation of the global economy, first, as a self-reinforcing system capable of autonomous expansion and increasing complexity, which fundamentally changes the logic of its current functioning. Second, it may be understood as a transition to a qualitatively

new state in which autonomous algorithmic systems become the principal driver of economic evolution.

The conducted analysis demonstrates that the evolution of research on economic singularity is currently taking place with an emphasis on such related areas as the AI economy, automation, digital platforms, and quantum economy. Thus, during 2005–2015, studies devoted to singularity focused on the theoretical prerequisites for the formation of the concept of *Technological Singularity* in the context of the impact of AI on the economy (the economy remained human-centered, but technologies began to transform market structures).

During the period 2015–2023, most studies concentrated on the analysis of platformization and the algorithmic economy, the impact of AI on productivity, the dominance of Big Tech, and the economics of data and algorithmic governance. Throughout this period, intensive scientific discussions took place concerning the "*post-labor economy*" and the formation of the prerequisites for singularity, while the focus of research shifted from the structuring of technologies to the analysis of their economic consequences, namely the transformation of the economy into a data-driven system. This concerns both comprehensive monographs [8; 9; 10] and periodical publications [11; 12; 13]. In recent years (2023–2025), the subject matter of scientific publications has changed fundamentally toward the protosingularity of the AI economy – the transition to *self-optimizing systems*, including the integration of AI and quantum technologies, autonomous systems, and self-learning economic models [14; 15; 16; 17].

Over the last several years, a number of studies by Ukrainian scholars directly devoted to the concept of "economic singularity" have also emerged. Thus, V. Opanasiuk and others [18; 19] examine "integrated singularity" (where AI surpasses human intelligence) through the prism of national readiness (education, research and development, policy) for potential exponential changes. S. Hromiak associates singularity with quality management paradigms [20].

In general, while Western publications prioritize empirical assessment and economic modeling aimed at measuring the impact of AI on economic development, Ukrainian authors focus on national strategies in the context of singularity. Ukrainian studies fill a specific niche by linking global AI trends with the national context, concentrating on conceptual frameworks

and national strategic scenarios, and relying more on scenario-based logic than on multilevel macroeconomic assessments. Regarding policy, Ukrainian scholars emphasize capacity building (digital infrastructure, STEM education, and balanced AI policy) as well as resilience under wartime conditions, whereas Western sources investigate the adaptation of education systems and labor markets to the new challenges of an unpredictable environment. Both research directions reveal knowledge gaps: Western studies identify policy implications in workforce retraining and antitrust legislation, while Ukrainian authors stress the importance of the quality of governance in digital infrastructure and education for achieving positive outcomes.

In his study of singularity, G. Snooks proposed using a graphical form to interpret the behavior of the exponential curve (a figurative description of the shape of the growth curve to denote the result of mathematical progression) [21]. This concept became known as the "*Snooks Vertical*," understood as a process (rather than a separate formula) in which the gradual growth of a system (economy, technology, etc.) subsequently transitions into accelerating exponential growth, and at a certain moment the curve takes the form of a vertical line. This resembles the classical exponential growth curve but emphasizes the final phase, where growth becomes practically "explosive."

Moreover, according to G. Snooks' theory, all elements of the system acquire new properties and change the nature of their interaction with one another, while certain moments in time become a kind of phase transition, after each of which a qualitative leap occurs within the system. The time intervals between these transitions progressively shorten according to a simple relationship, leading to exponential development and movement toward the point of singularity. He also argued that, according to calculations, humanity would reach the point of singularity in the second half of the twenty-first century, approximately from the beginning of the 2050s onward.

Another important concept relevant in the context of technological singularity is *NBIC convergence*, an acronym denoting four components: nano (N), bio (B), info (I), and cogno (C). In turn, "convergence" refers to the process of merging, rapprochement, or concentration of several entities into a single point. Essentially, convergence implies the merging of all

scientific disciplines into one unified field of knowledge. In futurological concepts, NBIC convergence is currently considered a key element in humanity's transition from the fifth to the sixth technological paradigm.

Each of the previous technological paradigms possessed its own distinctive features and phase transitions:

1) the First Industrial Revolution (from 1772);

2) the Age of Coal and Steam (from 1825);

3) the Second Industrial Revolution – the Age of Steel (from 1875);

4) the Age of Oil (from 1905);

5) the Scientific and Technological Revolution – the Age of Computers (from 1971);

6) the Age of Nanotechnology (from 2004, although the transition has only begun);

7) the Age of Cognitive Technologies.

At the same time, although the convergence of various scientific fields into one unified sphere is currently at an early stage, systems of knowledge also possess the property of differentiation – the transformation of one simple entity into multiple interconnected entities that interact through transactions. In some systems theories, this is referred to as a "system with irreducible complexity." An example is specialization and the division of labor: the more complex a system becomes, the more likely it is to consist of numerous isolated autonomous subsystems, each of which separately has no independent meaning. Thus, rather than convergence, the process often involves disintegration and specialization.

Therefore, the interpretation of the concept of convergence acquires particular significance, for example, in the context of the further segmentation of the labor market into specific professional subpopulations, where each individual is responsible only for a narrow field of knowledge and functions within its boundaries. Nevertheless, these constituent elements of a "distributed system of competencies" remain interconnected, forming a certain unified structure.

At the same time, despite the significant number of studies in the field of digital transformation and AI, including futurological modeling, the issue of the relationship between the autonomization of economic decision-making and the formation of economic singularity remains insufficiently developed. In particular, there is no holistic understanding of the relationship

between AI autonomy and macroeconomic singularity at the level of an interdisciplinary approach, nor of the mechanism of transition from the digital economy to a state in which interaction among autonomous systems becomes the determining factor in the development of the modern global economy.

2. Features of the Transformation of the International Economy under Conditions of AI Singularity

In recent years, due to the development of AI technologies, the problem of singularity has begun to occupy an important place in studies of economic growth. Indeed, superintelligent AI is beginning not only to write "technological code" for all possible production processes but also to improve itself by creating enhanced copies of its own systems without any human involvement. Until recently, this seemed like science fiction; however, today executives of leading IT companies believe that within the next 5–8 years AI will generate almost all code for modern software. According to data from *MIT Technology Review*, 94% of companies already use generative AI in the development of their products, while 82% employ it at several stages of the product life cycle. Gartner analysts estimate that the automation of routine tasks could increase developer productivity by 30% and add more than USD 1.5 trillion to global GDP [22].

Since the number of such AI systems that fully or almost fully replace humans can be expanded rather rapidly, this should lead to the transition of the economy into a regime of singularity, that is, to growth rates that continuously accelerate toward infinity. This refers to a future situation in which "the rapid development of information technologies and AI crosses the threshold beyond which economic growth begins to accelerate dramatically through technological improvements carried out at ever-increasing speed and cascading throughout the entire economy" [23, p. 299].

Unlike the partial replacement of humans by machines, which historically complemented human labor and multiplied its productivity (steam engines, electricity, or the Internet), the implementation of AI claims something more ambitious: the replacement of the unique ability inherent to humans – intelligence itself. Singularity may take different forms depending on the segment of the economy in which advanced AI becomes capable of completely replacing human labor. The economy may

enter a trajectory of "explosive" growth provided that, on the one hand, the elasticity of substitution between labor and capital sharply increases and the share of progressive sectors with continuously growing productivity expands rapidly within GDP. On the other hand, the share of tasks automated through AI will continue to grow, leaving humans with fewer and fewer directly performed tasks. Therefore, not all economists share the "super-optimistic" expectations regarding the interdependence between the progress of AI technologies and the multiple acceleration of economic growth rates.

In contemporary economic literature, the implementation of AI is also frequently described through terms such as "explosive," "super-exponential," or "transformative" economic growth, since under such conditions the speed of growth appears to be an order of magnitude higher than existing statistical indicators. The reason is that in a situation of singularity, production could begin to grow annually by at least 20–30% instead of the current 2–3%, a level that has remained virtually unchanged for countries at the technological frontier over the past century and a half, beginning from the final decades of the nineteenth century. In this context, AI is defined either as "the ability of a machine to imitate intelligent human behavior" or as "the ability of a particular artificial agent to achieve goals across a wide range of diverse environments" [24, p. 238].

Generative AI currently demonstrates one of the most uneven adoption trajectories in the history of technology. On the one hand, it is radically transforming the work of developers; on the other hand, most companies do not yet observe significant returns on their investments. A study by MIT showed that despite investments of USD 30–40 billion in the United States over the past four years, 95% of generative AI projects generate zero returns for companies [25]. According to the study, the outcomes were so sharply divided both among buyers (enterprises, small and medium-sized businesses) and developers (startups, vendors, and consulting firms) that the phenomenon was termed the "*GenAI divide*." Only 5% of pilot projects involving generative AI produce millions in returns, while the overwhelming majority remain without any measurable impact on profits or losses.

At the same time, tools such as ChatGPT and Copilot are being widely adopted: more than 80% of organizations have explored or piloted them, and nearly 40% report actual implementation. However, these tools primarily enhance individual productivity rather than overall

profit-and-loss indicators. Meanwhile, modern enterprise-grade custom system software solutions developed and sold by vendors exhibit the following demand characteristics: 60% of organizations evaluated such tools, 20% reached the pilot stage, and only 5% achieved full production deployment. Most projects fail because of unstable workflows, the absence of contextual learning, and incompatibility with current business operations.

However, for many researchers of technological history, the absence of an immediate effect represents a "normal" delay associated with the classical pattern of implementing breakthrough transformational technologies. The problem lies not in AI itself, but in the fact that companies attempt to apply it by "overlaying" it onto outdated processes rather than fundamentally restructuring business models, redesigning infrastructure (especially data platforms), and retraining personnel. Truly expected results can only be achieved when AI transforms from a simple automation tool into the core of a company's business processes, accompanied by the creation of new types of jobs and the expansion of employee capabilities.

Under current conditions, the architecture of AI consists of *three levels of capability*:

– Weak/Narrow AI – specialization in a single task (for example, recommendation systems or facial recognition);

– Strong/General AI – the ability to solve any intellectual task at the human level;

– Artificial Superintelligence (ASI) – AI that surpasses human intelligence in every field.

In addition, AI includes *four functional levels* according to the experience of its use (basic models, connection layers, AI agent management platforms, and user interfaces):

– Reactive machines – systems without memory that respond only to current stimuli (for example, Deep Blue);

Limited Memory – systems that use past experience for decision-making (for example, chatbots and autonomous vehicles);

– Theory of Mind – potential systems capable of understanding human emotions and beliefs; currently under development;

– Self-aware AI – AI possessing its own consciousness and emotions; still a theoretical and conceptual construct.

Approaches to AI classification also involve accounting for knowledge-based expert systems (Top-Down approaches: natural language processing – NLP, image and video analysis – computer vision, machine learning – ML, and deep learning) as well as the study of neural networks that imitate the functioning of the human brain (Bottom-Up approaches). According to information technology experts, AI is rapidly moving toward superintelligence.

Indeed, on the one hand, AI is fundamentally transforming the conditions of existence across all industries without exception. For example, assessing the safety of food products or the effectiveness of pharmaceuticals no longer requires tens of billions of dollars and thousands of human-years of research. Aggregated data from pharmacies, fitness centers, grocery stores, hospitals, bars, morgues, nightclubs, banks, and other market participants can provide answers within seconds with a high degree of reliability. On the other hand, within a "universal ethics neural network," a synergistic interaction emerges between natural and artificial formations of intelligence and consciousness, while sensory systems enable it to receive information about the surrounding environment. The creation of artificial self-awareness within such a neural network generates the capacity for autonomous learning and real-time adaptation. Since generative AI lacks human emotions, it becomes a reliable generator of arbitrary volumes of material wealth, limited only by the availability of energy resources. Moreover, the pendulum-like shift from irrational euphoria to equally irrational panic (for example, in stock trading), which previously caused fundamental market imbalances and recurrent crises, is being modified under the influence of AI.

Modern AI already has enormous potential to reconfigure the economy through the automation of a significant number of tasks currently performed by humans, and its implementation is effectively a new form of automation [26]. Although "the Internet is also an example of automation that accelerates the production of ideas" [27, p. 146], AI occupies a special position – it does not merely increase the efficiency of researchers and inventors, but potentially replaces them entirely. According to experts at Goldman Sachs [28], in frontier economies AI could add an additional 1.5 percentage points to annual per capita GDP growth over the next decade, while McKinsey estimates [29] suggest 1.5–3.4 percentage points. This implies, in effect, a 1.5–2 times acceleration of economic growth. However, some economists

go further, arguing that within the next ten years AI could increase GDP in developed countries by 100% in the baseline scenario and by up to 300% in a more "aggressive" scenario [30]. This is, of course, not yet singularity, but it represents a rapid approach toward it. Thus, in the current century, economic growth rates may accelerate tenfold or more, and the formal conditions for transitioning to a hypothetical state of singularity within existing growth models are fully open to analysis.

Platformization and digitalization of the economy are stimulating the mass adoption of autonomous AI agents and the delegation of decision-making in finance, logistics, and production, leading to the formation of an economy without a "center," new markets and submarkets, and a partial decline in the importance of traditional market institutions. Existing theories do not adequately explain the "jump-like" nature of these changes, and this "tipping point" in the conceptual evolution of singularity raises the question: "Can the autonomy of economic decision-making be considered a trigger of singularity?"

One of the key transformations of the modern global economy is the gradual formation of a new type of economic agent – the autonomous AI agent – which, unlike traditional market participants, operates based on algorithmic models capable of self-learning, adaptation, and decision-making without direct human intervention. The essential precondition for the emergence of autonomous AI agents is the process of delegating economic decisions from individuals to algorithmic systems. While in the early stages of digitalization AI performed auxiliary functions (data analysis, forecasting), the current stage is characterized by a transition toward operational autonomy.

This process unfolds across several levels: (a) analytical delegation (AI processes large datasets and generates recommendations); (b) tactical delegation (algorithms select optimal actions under given conditions); (c) strategic delegation (systems independently define goals and methods for achieving them within specified constraints). As a result, a situation emerges in which a significant share of economic decisions is made faster, more accurately, and more efficiently. At the same time, this reduces transaction costs but also creates conditions for the loss of (primarily human) control over certain segments of the economic system.

Indeed, from the perspective of endogenous economic growth theory by R. Lucas [31] and P. Romer [32], technological progress is considered an internal outcome of economic functioning. Within this paradigm, knowledge, innovation, and human capital are the key drivers of growth. In the case of autonomous AI agents, this logic evolves further – knowledge is generated not only by humans but also by algorithms, the learning process becomes automated, and the innovation cycle becomes continuous and self-reinforcing. Thus, AI systems act as an endogenous mechanism of knowledge production, extending the classical endogenous growth model to a level of "algorithmic endogeneity." This allows for the formulation of a principle: the economic system no longer merely uses knowledge – it autonomously produces and scales it.

The next stage in the evolution of economic singularity is the transformation of AI from a tool into an independent market participant. Autonomous agents acquire features of economic subjectivity – from decision-making processes (buying, selling, investing) and interaction with other agents (including other AI systems) to adaptation to market environments and optimization of their own behavior based on experience. This gives rise to a new form of economic interaction – the "AI-to-AI economy" – where key transactions occur without direct human involvement, and the market evolves from a space of human decisions into an environment of algorithmic competition (processing speed, quality of machine learning models, access to data). Instead of traditional competition between companies or states, competition emerges between algorithmic ecosystems, fundamentally altering the nature of competition itself.

The interaction of autonomous agents can be interpreted within the framework of complex adaptive systems, where the economy is seen as a network of interacting elements capable of adaptation and self-organization. In this context, each AI agent is an adaptive unit, and their interaction generates emergent system properties in which the macro level (international markets, the global economy) is the result of micro-level algorithmic interactions. A key feature of the current stage is that the speed of these interactions significantly exceeds human decision-making speed, "pushing" the system toward dynamic instability and phase transitions – core concepts in complexity theory.

The current formation of autonomous AI agents is most evident in sectors characterized by high-speed decision-making and large data volumes. In finance, algorithmic systems already perform asset management, risk assessment, and credit scoring. Autonomous agents can independently construct investment portfolios, adapt strategies to market changes, and execute transactions in real time, gradually displacing traditional financial intermediaries and forming algorithmically governed financial ecosystems. In logistics and supply chains, systems increasingly coordinate with each other (e.g., warehouse systems, transport platforms, and production modules), forming self-regulating logistics networks. AI agents also enable automated route planning, inventory optimization, and coordination among supply chain participants, significantly increasing efficiency while reducing transparency of decision-making for human operators.

A particularly illustrative case of AI-to-AI interaction is algorithmic high-frequency trading. This involves decisions made in milliseconds in environments where humans cannot intervene in real time, and algorithms compete on speed and precision. In such a setting, the market effectively functions as a system of interacting algorithms, creating conditions for phenomena that are difficult to capture using traditional economic models (such as sudden crashes or "flash crashes"). Thus, autonomous AI agents in trading, finance, and logistics are gradually transforming from auxiliary tools into full-fledged economic actors, reshaping the structure and logic of global economic relations. The delegation of decision-making to algorithms, the emergence of AI as a market participant, and the further diffusion of such systems across key economic sectors create the preconditions for a new stage of economic singularity, where interaction between algorithms becomes the dominant mechanism of economic coordination.

3. Singularity Transformations of the Economy under Super-Exponential Growth

From a quantitative perspective, modern economic science distinguishes *three main types of economic growth*: exponential growth (the economy grows at a constant rate year by year, for example 3%), super-exponential growth (the growth rate increases continuously over time: 2% in the first year, 3% in the second, 4% in the third, and so on), and sub-exponential growth (the economy grows at a continuously declining rate: 1% in the

first year, 0.5% in the second, 0.2% in the third, etc.). While most growth models (within growth theory) have focused on explaining exponential growth, super-exponential and sub-exponential cases have often been treated as peripheral. Their theoretical possibility has been acknowledged, but they have attracted relatively little attention from researchers. This situation changed in the early 21st century, when real prospects of both super-exponential growth – driven primarily by AI – and sub-exponential dynamics emerged on the horizon, especially for economies at the technological frontier.

In general, two types of singularity are distinguished: Type I and Type II. In the first case, growth accelerates continuously over an unlimited period of time; in the second, infinite growth occurs within a finite time interval. Type II singularity is usually associated with science fiction (although some formal growth models allow it), whereas Type I singularity is considered practically attainable. A more plausible scenario is one in which growth rates continuously accelerate over a bounded but sufficiently long period (for example, several decades), after which they stabilize at a certain level. It is worth noting that "explosive" growth at an annual rate of around 30% has never been observed in world economic history – not in England during the Industrial Revolution, not in Japan in the 1960s, and not in China in recent decades. Existing projections suggest the following: global GDP currently doubles approximately every 20–30 years; under "explosive" growth conditions, it could double every 2–3 years. According to T. Davidson, this would imply "the creation and deployment of such a multitude of technological advances that living standards would improve ten times faster than anything ever developed in human history" [33].

According to this assumption, all improvements in housing, healthcare, software, and related fields that currently take 10 years could be achieved within one year. Similarly, scientific progress in physics, biology, engineering, and social sciences that currently requires a decade could be achieved within a single year. In some sectors, growth would be faster, in others slower, but on average it would accelerate tenfold. As a result, within 10 years humanity could achieve technological and economic progress comparable to what was previously achieved over 100 years. It is currently difficult even to imagine how rapidly AI would transform human life and welfare under super-exponential growth conditions. At 30% annual growth

rates, humanity would become 1,000 times wealthier within 25 years – while historically living standards have increased only about 100-fold over the entire course of human history. If such a growth rate were sustained over a century, per capita income would increase by 250 billion times, which, while not singularity in the strict sense, is practically indistinguishable from it [33].

In all economic growth models, output is defined as a function of production factors (the Cobb–Douglas function): output depends on capital, labor, and total factor productivity (TFP). These models assume diminishing marginal returns, meaning that each additional unit of capital (holding labor constant) and each additional unit of labor (holding capital constant) generates a smaller increase in output. Diminishing returns significantly constrain the growth potential that production factors alone can generate. A large body of empirical research shows that, in the long run, the main contributor to GDP growth is TFP rather than accumulation of physical or human capital. From this perspective, idea-based models appear more adequate than accumulation-based ones.

Returns to scale refer to the change in output when all inputs increase proportionally. They can be constant (doubling all inputs doubles output), increasing (doubling inputs more than doubles output), or decreasing (doubling inputs less than doubles output). By doubling the number of factories – and thus capital and labor – we could double output. However, "explosive" (super-exponential) growth scenarios assume increasing returns to scale.

Ideas, knowledge, and technologies are examples of non-rival goods: their use by one agent does not prevent simultaneous use by others. Because of this non-rivalry, they generate increasing returns to scale, which under certain conditions can lead to singularity-like dynamics with continuously accelerating growth rates. For example, in the Cobb–Douglas production function, capital is treated as an endogenous factor since it can be accumulated through savings and reinvestment. Labor and technological progress, however, are typically treated as exogenous factors determined outside the model. As a result, long-run economic growth is driven primarily by these exogenous components – labor and technology.

F. Trammell and A. Korinek examined 25 alternative ways of incorporating AI into formal growth models, each conceptualizing technological progress

differently [34]. If advanced AI systems can effectively replace humans both in producing "goods" and in producing "ideas," this could become a source of explosive growth by generating increasing returns to scale from accumulating resources. These three general arguments – historical experience, positive feedback in idea production, and the possibility of singularity within standard growth frameworks – are sufficiently strong to avoid dismissing super-exponential growth as implausible and instead to treat its realization within coming decades as a realistic scenario.

The most general argument against the idea of singularity is the so-called *Baumol cost disease*, which may become a structural barrier to "explosive" economic growth. This phenomenon was first identified by the American economist W. Baumol, after whom it is named [35]. According to Baumol and his followers, different sectors of the economy exhibit different levels of susceptibility to technological progress: in some, productivity grows rapidly, while in others it grows slowly or remains constant. As a result, over time, high-productivity sectors tend to occupy a smaller share of GDP, while low-productivity sectors occupy a larger one. Since overall economic growth is a weighted average of sectoral growth rates, increasing dominance of stagnant sectors slows aggregate growth. Empirical evidence broadly supports this mechanism, showing that sectors with declining productivity growth tend to expand their share of GDP over time.

However, the Baumol cost disease scenario is not the only possible outcome (at least in theory). To describe the opposite case, W. Nordhaus introduced the concept of "Baumol's euphoria" [23]. This refers to a situation in which demand shifts toward sectors with rapidly growing productivity, increasing their share of GDP and further accelerating overall economic growth. Which scenario ultimately prevails – Baumol's cost disease or Baumol's euphoria – depends on the elasticity of substitution between goods produced in low-productivity and high-productivity sectors.

According to the "bottom-line" assessment, the conclusions are more or less objective: if technological progress occurs, first, through the continuous improvement of AI systems, and second, through an increasing elasticity of substitution of labor by informational capital embodied in these systems, then sooner or later the economy will enter a trajectory of "explosive" growth. Under these conditions: (1) the share of informational capital in the value of production resources will continuously increase, approaching

the limit of 100%; (2) its contribution to GDP will also steadily rise, approaching 100%; and (3) its continuously accelerating growth will be capable of driving accelerated growth of the entire economy. Moreover, even in this scenario, full replacement of workers by AI systems will not be required: super-exponential growth will be achievable even under partial automation, albeit at a sufficiently high level. According to W. Nordhaus, it would be sufficient to automate 80% of all tasks currently performed by workers (although, given current trends, even approaching this threshold is, in his view, projected only beyond the horizon of the 21st century) [23].

Certain tasks may remain non-automated even if their automation is technically possible, due to the fact that consumers may prefer that they be performed by people in certain professions (athletes, clergy, in-home caregivers, etc.). In other words, people may prefer interaction with human doctors, human teachers, and other service providers that carry high symbolic value [36]. Although computer programs already play chess better than the greatest grandmasters, this has not led to the closure of chess tournaments, since there remains an interest in human competition rather than machine competition. It is unlikely that people will want sermons in churches to be delivered by robot priests, or actors in films to be replaced by robot performers – even when this becomes technically feasible.

"Explosive" growth rates of around 20–30%, under otherwise equal conditions, would require Schumpeterian "creative destruction" on an accelerated scale. With productivity doubling every 2.5 years, substantial portions of physical and human capital would become rapidly obsolete. Each year would require both the radical restructuring of infrastructure – dismantling large parts of existing equipment and installing new systems – and the retraining of a significant share of the workforce. According to the Schumpeterian approach, incentives for innovation are linked to the ability to capture rents from temporary monopoly power enjoyed by innovators, protected through patents, trade secrets, and similar mechanisms. If AI facilitates the copying of innovations, competitors would benefit, while innovators would lose, since the period of rent extraction from new technologies would be shortened.

Energy singularity, in the context of economic singularity, becomes one of the drivers of broader economic transformation alongside AI, automation, and new materials. It is a hypothetical moment when energy becomes

so cheap, accessible, and practically inexhaustible that it fundamentally transforms the economy, similar to how technological breakthroughs reshape society in concepts of economic singularity. The term was first introduced by J. Cordeiro [37], who argued that cheap energy changes production: it triggers a sharp "jump" in productivity and a "collapse" in the cost of many goods, restructures global supply chains, increases the importance of recycling, and reduces incentives to relocate production to countries with cheap labor.

In subsequent (modern) conceptual studies [38; 39], the notion of "energy singularity" is analyzed, on the one hand, as a function integrating nuclear fusion, renewable energy sources, energy storage, and AI optimization, with exponential growth in energy generation as a key factor. On the other hand, it is treated as a predictive hypothesis – a multidisciplinary futurological concept based on energy research in the context of a transition toward energy abundance.

There is also the concept of "*bioeconomic singularity*," which conceptually corresponds to a transition toward a fully bio-based economy, the substitution of fossil resources with biological ones, and exponential growth in biotechnology [40]. In terms of a formalized model, bioeconomic singularity is a function integrating biotechnology, AI, biomass, and cyclical systems. It is also a specific hypothetical moment when advances in synthetic biology make production so cheap, scalable, and universal that it radically reshapes the economy (just as steam engines or electricity did during the Industrial Revolutions). In this sense, biology becomes a universal production platform – bacteria produce materials (bioplastics, "grown" tissues, new composites), cells become "factories for accelerated organism design" (fermentation-based proteins), old industries lose relevance, and production shifts from factories to bioreactors (an analogue of the transition from 20th-century mechanics to 21st-century software). Key drivers of development become data (genetic), design, and intellectual property, rather than land, labor, and raw materials [41].

Today, the bioeconomy is based on the use of biological resources for the production of energy, materials, and services, and represents a transition toward a renewable economy grounded in the integration of ecology and social governance. In turn, the bioeconomic singularity treats biology as a programmable production platform, stimulating a shift from a "extract and

harvest" model to a "grow and synthesize" model. Currently, more than 60 countries in the global economy have their own bioeconomy development strategies. According to existing scenarios, the full transformation of the global chemical industry, energy sector, and agriculture will require investments of USD 1–2 trillion annually by 2050, which is approximately 1.3–2.6% of global GDP [42]. For example, in the European Union, the scale of bioeconomy development is turning it into a macro-sector of the global economy, whose accelerated growth is a precondition for singularity. The estimated value of the EU bioeconomy, including goods and services, is EUR 2.7 trillion; annual growth rates of the biotechnology sector reach 18%, exceeding EUR 720 billion; 17.1 million jobs in the EU are created in biomass production and processing alone, generating 5% of GDP; and for every job created in the bioeconomy, there are 2.9 additional jobs created [43].

A full-fledged bioeconomic singularity occurs under the condition that 80–90% of bio-renewable energy and biologically derived materials operate in closed-loop cycles (zero waste), and biotechnology becomes cheaper than traditional technologies [44]. As a macro-level forecasting concept, the bioeconomic singularity is based on the exponential development of biotechnology and a transition toward a circular economy growing at double-digit rates. However, the shift toward bioeconomic dominance is constrained by strict environmental and resource limitations. At the same time, there is currently no unified measurement framework, which is characteristic of an early-stage systemic transition (a pre-singularity phase), although the bioeconomic and energy "singularities" together create a self-accelerating economy in which innovations objectively generate multiplicative increases in further innovations.

The *cognitive singularity* is a hypothetical moment when human attention, thought, and intelligence become, on the one hand, the primary economic resource, while the boundary between human and machine intelligence effectively disappears. On the other hand, these capacities become so manageable, enhanced, and integrated with technology that they radically reshape the economy (as profoundly as energy or production in the energy and bioeconomic "singularities"). The concept of cognitive singularity is typically considered an aspect of technological singularity: intelligent systems (AI/AGI) surpass human cognitive capabilities and

enter a regime of self-accelerating development (an intelligence explosion). In effect, the economy begins to revolve not around labor or existing resources, but around attention, thinking, and consciousness through the combination of the attention economy (which can be measured, optimized, and amplified), neurointerfaces, and AI. If in Industry 4.0 the scarce resources were labor and capital, in Industry 5.0 the scarce resources become high-quality attention and original thinking. At the same time, the speed of cognitive processes increases, new factors of production emerge – real-time intelligence and a "market of cognitive states" – and the boundary between humans and machines is blurred.

The concept of cognitive singularity emerges at the intersection of research in artificial intelligence, cognitive science, and the philosophy of technology, and forms part of the broader framework of technological singularity. First, it is defined as a hypothetical developmental state in which artificial intelligence systems reach or exceed human intelligence and acquire the capacity for autonomous self-improvement, leading to exponential growth in cognitive capabilities. Second, it is considered a consequence of the so-called "intelligence explosion," with the main mechanisms of this process being machine learning, recursive self-improvement, and the scaling of computational resources [45].

In contemporary research [46; 47; 48], this is interpreted as a transition toward superhuman intelligence associated with the emergence of autonomous self-improving systems and a transformation of the cognitive architecture of society (human + AI). The interdisciplinary field of "singularity studies" encompasses AI, neuroscience, cognitive science, sociology, economics, ethics, and law. The exponential development of AI is driven by increasing computational power and data availability, leading to faster learning and modeling and a transition from narrow AI to multi-task systems. Key constraints include the absence of genuine AI consciousness, limited model interpretability (the XAI problem), and dependence on human-generated data. Key indicators of approaching singularity include decision-making autonomy, self-improvement capability, integration of learning and reasoning (neuro-symbolic AI), and the potential emergence of AI consciousness or its functional analogues.

On the one hand, AI systems already possess components traditionally associated with cognitive singularity (autonomous decision-

making and self-development capabilities, generalization ability, and generativity – the creation of new knowledge and content). On the other hand, AI's ability to surpass human expert knowledge in narrow domains, the shift from algorithmic to heuristic-cognitive approaches, and the absence of fundamental physical barriers to superintelligence development are all notable. At the same time, a key ethical issue remains – forms of control (AI alignment), contradictions, and the probability of rapid transition to superhuman intelligence levels [49; 50].

Since risks grow proportionally with system capabilities, functional indicators of machine "consciousness" are being proposed based on AI computational resources (which double faster than Moore's Law). This leads to exponential growth in data volumes alongside nonlinear improvements in algorithmic efficiency. Despite significant progress, several problems remain unresolved: (a) the absence of artificial general intelligence (AGI); (b) limited model interpretability; (c) dependence on large-scale data. Currently, predictive models (scenarios) of cognitive singularity develop along the following directions:

1. Intelligence explosion (rapid self-improvement of AI leads to uncontrolled growth of intelligence).

2. Human–AI co-evolution (formation of hybrid cognitive systems – human-AI coupling – via brain-computer interfaces and "augmented extended intelligence").

3. Institutionally controlled development (AI regulation through international legal mechanisms).

Through three key components – (1) direct brain–machine interfaces enabling thought-to-action without keyboards and accelerating decision-making; (2) enhancement of cognitive abilities via memory, concentration, and learning augmentation; and (3) new forms of labor ("thinking as a service" and collective cognitive networks) – the role of neurointerfaces is rapidly increasing. This fundamentally transforms the economy. First, labor becomes less physical and routine and more cognitive, with part of thinking delegated to AI. Second, an "intelligence market" emerges, initially based on real-time expert task decomposition as modular units of thinking. Third, learning barriers disappear: with neurointerfaces, knowledge can be acquired rapidly, making learning almost instantaneous. Fourth, new business models emerge based on deep monetization of

attention, subscriptions to cognitive enhancement, and "packages of thinking" (skills-as-a-service).

At present, cognitive singularity interacts with energy singularity (providing infrastructure) and bioeconomic singularity (providing biological tools for the brain), and together they form a self-organizing economy in which energy, matter, and intelligence are nearly unconstrained, while production, biology, and cognition converge. Simultaneously, a feedback loop effect emerges, in which all three "singularities" interact as a unified system in a repeating cycle: AI improves biology → biology improves the brain → enhanced brains create better AI → cheap energy scales all processes. Thus, energy singularity provides scale, bioeconomic singularity provides material flexibility, and cognitive singularity provides speed and direction.

Accordingly, the cognitive singularity is a scientifically grounded but empirically unverified hypothesis. Current AI development demonstrates the presence of key prerequisites: autonomy, self-learning, and scalability. Leading international studies confirm the possibility of transitioning toward superhuman intelligence, while emphasizing issues of control and regulation. The most likely scenario is a gradual cognitive integration of humans and AI, rather than a sudden "intelligence explosion." Future research should focus on developing safe AGI (AI alignment) and its legal regulation within ethical frameworks for AI use.

CONCLUSIONS

The conducted research demonstrates that the contemporary stage of global economic development is characterized by the transition from a linear, human-centered economic model toward a nonlinear, algorithmically governed system based on artificial intelligence, autonomous agents, and self-learning technological ecosystems. The convergence of digitalization, AI technologies, quantum computing, platformization, and data-driven governance forms the foundation of a new neotechnology paradigm of global development associated with the emergence of economic singularity. The main conclusions of the study are as follows:

Economic singularity should be interpreted as a systemic phase transition of the global economy rather than solely as a technological phenomenon. Its defining characteristics include exponential and super-exponential

growth dynamics, increasing autonomy of technological systems, algorithmic governance, and the gradual displacement of human-centered economic coordination mechanisms.

The proposed Economic Singularity Framework (ESF) conceptually explains the transition from the classical economy toward the digital economy, AI economy, autonomous economy, and ultimately economic singularity. The key drivers of this transformation are artificial intelligence, quantum computing, informational capital, data intensity, and institutional adaptability.

Autonomous AI agents are becoming a fundamentally new type of economic actor within the international economy. Unlike traditional market participants, they possess the capacity for self-learning, adaptation, autonomous decision-making, and interaction with other AI systems without direct human intervention. This creates the prerequisites for the formation of an AI-to-AI economy in which algorithmic ecosystems increasingly replace traditional forms of market coordination.

The study substantiates that endogenous technological progress generated by self-learning AI systems fundamentally transforms the logic of economic growth. Knowledge production becomes partially autonomous, while innovation cycles acquire self-reinforcing and cumulative characteristics. As a result, the economy evolves into a complex adaptive system governed by nonlinear dynamics and positive feedback loops.

The emergence of super-exponential growth trajectories becomes theoretically possible due to increasing returns generated by informational capital and non-rival technological goods. Under such conditions, the contribution of AI-driven informational capital to GDP and productivity growth continuously increases, creating the foundations for accelerated structural transformation of the global economy.

The interaction between economic singularity, energy singularity, bioeconomic singularity, and cognitive singularity forms an integrated self-accelerating system of technological evolution. Energy abundance, programmable biology, neurointerfaces, and AI-driven cognitive enhancement collectively reshape production systems, labor markets, global value chains, and mechanisms of value creation.

The transformation of the global economy under conditions of singularity generates both opportunities and systemic risks. On the one hand, AI-driven

technologies may significantly increase productivity, reduce production costs, accelerate scientific progress, and improve living standards. On the other hand, they intensify technological inequality, concentration of economic power within global Big Tech ecosystems, institutional asymmetries, and ethical challenges related to algorithmic governance and loss of human control.

Traditional economic theories and institutional mechanisms are increasingly unable to adequately explain or regulate the nonlinear and self-organizing dynamics of the emerging AI economy. This necessitates the development of new interdisciplinary approaches combining economics, complexity theory, technological forecasting, international political economy, ethics, and global governance studies.

For countries participating in international economic relations, strategic competitiveness will increasingly depend not on traditional industrial advantages but on access to data, AI infrastructure, computational resources, digital ecosystems, and the ability to integrate into global technological networks. Consequently, the architecture of future international competition will shift from state-centered competition toward competition between algorithmic ecosystems and technological platforms.

The future trajectory of economic singularity will largely depend on the effectiveness of international regulation, AI governance mechanisms, ethical standards, institutional flexibility, and the capacity of societies to adapt to rapidly accelerating technological transformations.

Prospects for further research should focus on several directions: the development of formal macroeconomic models of economic singularity; quantitative assessment of AI-driven productivity effects; analysis of institutional adaptation under conditions of algorithmic governance; investigation of AI alignment and international regulation mechanisms; and the study of geopolitical transformations associated with technological asymmetries and the global concentration of informational capital. Particular attention should also be devoted to the interaction between cognitive, bioeconomic, and energy singularities within the emerging architecture of Industry 5.0 and the future world economy.

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