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NANOTECHNOLOGY AND AI AS A CHALLENGE FOR DEVELOPMENT IN SEMI-PERIPHERAL AND PERIPHERAL COUNTRIES[1]

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Abstract

This chapter discusses the implications of integrating nanotechnology and AI in the relationship between the capitalist production system's core, semi-peripheral, and peripheral countries. Structural elements allow the countries of the center to maintain a hegemony in the development of knowledge, patents, startups, and investment that leaves both semi-peripheral and peripheral countries on a path toward technological dependence. AI and nanotechnology converge through nanoelectromechanical systems (NEMS) and make possible the function of nanosensors, whose technological power comes to reconfigure productive and economic chains with several consequences that deepen the inequality between countries of the center, periphery, and semi-periphery. We structure the work by presenting essential information about the development of

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these strategic technologies and discussing the consequences in terms of the development perspective for non-hegemonic countries. The structural character of the relations of technological development in capitalism makes it complex for peripheral and semi-peripheral countries to deploy a process of sovereign technological development through AI and nanotechnology.

Key Words: *Center-semi-periphery-periphery; nanotechnology and AI; Nanosensors; technological underdevelopment, World System Theory.*

Introduction

The problem of development or progress in peripheral and semi-peripheral countries is often linked to a need for more technological advancement. In the global structure, where the processes of capital accumulation dictate the trajectory of technological advancement, new technologies are promoted with the hope of accelerating the capture of profits and increasing economic competitiveness. In this logic, central or hegemonic countries' efforts are deployed to insert themselves advantageously into these circuits of accumulation. Currently, nanotechnology and AI stand out as tools that can make possible the leap in development that peripheral and semi-peripheral countries seek. However, structural mitigating factors, mainly economic, may impede the achievement of this goal. This chapter addresses the structural conditions in the research and development of these technologies that act as a barrier to developing these countries. In the first part, we provide a theoretical review of the essential aspects that guide the discussion in the chapter. We highlight key aspects of World Systems Theory and discuss how to analyze technological development's subjective and objective relations conceptually. In the second section, we address the most critical aspects of the drive for nanotechnology at the global level, highlighting the leadership of the countries of the center. We do the same in the following section but about the convergence of AI and nanotechnology through the production and commercialization of nanosensors. We then close the chapter with a section of conclusions.

1. Technological Dependency of Peripheral and Semi-Peripheral Countries

The World-Systems Theory, developed by sociologist Immanuel Wallerstein (1974, 1979, 1984), offers a framework for understanding the global economy and the relationships between countries in the context of the capitalist production system. This theory expands on the notion that some countries benefit while exploiting others through global economic and trade circuits; it also has a three-level hierarchy: core, periphery, and semi-periphery (Wallerstein, 2020). According to World-Systems Theory, Central (Core) countries are economically powerful nations that dominate global trade, finance, and technology. Examples include the United States, Western European countries, and Japan. They benefit the most from the global economic system, extracting resources and labor from peripheral countries to fuel their high-technology industries. Peripheral countries, on the other hand, are economically dependent and exploited by central countries. They often have weak economies, limited industrialization, and rely on exporting raw materials and cheap labor. Examples include many countries in Africa, Latin America, and parts of Southeast Asia. Semi-peripheral countries occupy an intermediate position, exhibiting characteristics of both central and peripheral countries. They have some industrialization and economic strength but are less dominant than central countries. Examples include Brazil, South Korea, and India.

The center-periphery concept originated as part of economic theories of the Economic Commission for Latin America (ECLAC) of the United Nations (UN); in the 1950s, Raul Prebisch led the way in this effort. According to this theory, the economic future of peripheral countries is intertwined with that of central countries, perpetuating underdevelopment through unequal exchange: while the peripheral countries expanded their trade through raw materials or commodities, the countries of the center manufactured goods with higher value-added, including those of high technology (Prebisch, 1986). Under this theoretical body, the location and functionality of a country's economic and scientific-technical potential in the global economy determine the basis and nature of technological dependence.

Both the World System and the Center-Periphery theory provide the analytical framework for analyzing the relationship between nanotechnology and artificial intelligence in the logic of global accumulation. Of course, this has systemic implications for the configuration of value transfer inequalities between the center, the semi-periphery, and the periphery.

The infrastructure, education, and Science and Technology (S&T) skills in central countries have been developed over several decades, with particular attention to the technological advancements in fields such as informatics, computers, biotechnology, and telecommunications. However, semi-peripheral and peripheral countries lack the necessary infrastructure and professional training to embark on the path of the knowledge economy. Therefore, one proposed solution is to develop a top-down mechanism or a "knowledge enclave" development scheme, where developing countries can create "Centers of Excellence" - institutes or research bodies with a few researchers but significant resources and a strong relationship with industry (Zayago, Foladori & Rushton, 2009).

Central countries, typically located in the developed regions of North America, Western Europe, and East Asia, have historically been at the forefront of technological innovation. These nations benefit from robust research and development (R&D) infrastructure, well-established educational systems, and capital and skilled labor access. As a result, they maintain a dominant position in shaping global technological trends and reaping the economic benefits accompanying innovation. Technological advancements from central countries often have far-reaching impacts across various sectors and geographies. For instance, breakthroughs in information technology, biotechnology, and renewable energy have revolutionized industries worldwide, driving productivity gains and facilitating interconnectedness in the global economy. Examples include Silicon Valley in the United States, known for its innovation ecosystem fostering the development of cutting-edge technologies, and Germany's leadership in engineering and manufacturing excellence.

In contrast, periphery and semi-periphery countries face significant challenges in technological development, primarily in Latin America, Africa, and parts of Asia. Gereffi (2008) argued that these nations often have limited resource access, underdeveloped infrastructure, institutional deficiencies, and socioeconomic disparities. Consequently, they need help to compete with center countries regarding technological innovation and integration into global value chains. Frontier research agendas are defined by the interests of the central countries, which leaves countries in the semi-periphery and periphery in a subordinate position, i.e., to follow the central countries' research and technological development priorities. However, peripheral and semi-peripheral countries are full of technological capabilities. Many nations possess untapped potential and unique strengths, such as abundant natural resources, diverse talent pools, and cultural richness.

To overcome technological barriers and harness their potential, peripheral and semi-peripheral countries have pursued various strategies. These include investing in education and skill development, promoting indigenous innovation and entrepreneurship, fostering international collaborations, and leveraging foreign direct investment and technology transfer initiatives. For example, since the early 2000s, countries like India and China have emerged as global hubs for technology outsourcing and manufacturing, capitalizing on their large labor pools and expanding domestic markets (Dahlman, 2007).

Capital accumulation at the global scale is pivotal in shaping technology diffusion across borders and leveling the playing field between center, semi-peripheral and peripheral countries (Marginson & Xu, 2023). Transnational corporations, operating across multiple jurisdictions, serve as conduits for technology transfer and knowledge spillovers, facilitating the spread of innovation to previously marginalized regions. Moreover, international trade agreements and intellectual property regimes influence the terms of technology exchange and incentivize collaboration between developed and developing economies.

However, the globalization of technology also raises concerns about unequal power dynamics and exploitation, as center countries often dictate the terms of engagement and reap disproportionate benefits from intellectual property rights and market access. For instance, the digital divide persists, with disparities in internet connectivity and digital literacy exacerbating inequalities within and between nations (Van Dijk, 2020). This trend has been amplified since the COVID-19 pandemic, which has left the peripheral countries in a more precarious technological position (Mishi, & Anakpo, 2022).

When the socio-economic conditions are favorable, labor, the primary productive force and main source of surplus value can improve its position in the system by furthering knowledge and intellect. Nowadays, we have moved beyond the accumulation of uncoordinated and random empirical knowledge to the concrete implementation of scientific discoveries as means of production (technology). At the structural level within the worldwide economy, noted by Farisov (1984), it is essential to understand that knowledge and technological production enable the dominant players in the global economy to exert significant control over the production processes of less developed countries. This structural condition widens the gap between the level of development of the central productive forces and those of both peripheral and semi-peripheral countries, deepening the asymmetrical interdependence between them on a larger scale. Historical and structural factors take work to overcome, which cause non-dominant countries to maintain a continuous technological dependence on their central counterparts. Aspects such as knowledge accumulation, financing, infrastructure, patents, monopolization of profits, and industrial platforms determine, to a large extent, the trajectory of technological dependence in these countries.

When analyzing the economic system's structure, it is essential to distinguish between objective and subjective production relations, as they largely explain the conditions of technological dependence (structural and promoted). The terms "subjective" and "objective" describe whether an activity is consciously driven or can be performed independently of consciousness. Foladori (2022) discusses this issue in a way that explains this difference through the ideas of "ideal relations" (subjective, voluntary) and "material relations" (objective, necessary). The contrast between idealism and materialism has been a conflicting point of debate in both philosophical studies and political economy.

-On one hand, the subjective analysis of productive relations focuses on personal opinions and perspectives. Since the early 20th century, the rapid social division of labor has established an "epistemological hegemony" that promotes capitalist accumulation. This approach examines reality without considering the historical and structural forces and interests that influence class formation and the creation of surplus value. It advocates for policy implementation based on the division of interests of different social groups and the overestimation of the rationality of individual actors without considering structural and historical factors (Záyago Lau, 2021). In today's hyper-specialized, globalized, and interrelated world, knowledge and methods focus on solving specific problems from areas or disciplines. To succeed, individuals must be highly competitive. As a result, higher education systems are now training spaces for producing highly qualified technicians who can assist the dominant class in capital accumulation. Within this systemic logic, a continuous influx of cadres and highly qualified personnel join the production areas of the central countries. "Brian drain" is a drawback that perpetuates the problem of technological dependence in underdeveloped countries, and the phenomenon has been widely studied within national, regional, and international settings (Kannappan, 1968; Arocena & Stutz, 2006; Bennassy & Brezis, 2013; Khan, 2021).

On the other hand, the objective analysis of productive relations considers historical, economic, and political contradictions at any given moment. This critical framework helps us understand how capitalism imposes technological relations from the dominant social relations of production, as explained by Rubin in 2019. Technological progress is controlled by two dominant factors: the pursuit of profit and competition. The laws of capital accumulation, therefore, determine what and when new knowledge or a new technology enters the productive system. Hence, technology becomes an essential instrument for capitalist accumulation in terms of incrementing competitiveness and profits. This structural condition creates a historical and structural feature on how Capital undertakes technology. As Marx (1973, p. 704) argues: “Invention then becomes a business, and the application of science to direct production itself becomes a prospect which determines and solicits it”. As technology and science advance within capitalist development, issues such as risks to health or the environment, labor displacement, pollution, exploitation, and monopoly are often overlooked.

Another essential aspect in furthering technological dependence between central and peripheral countries is private knowledge appropriation, as science and technology are not created in a vacuum. They result from centuries of knowledge accumulation. Each technology used in production embodies a wealth of knowledge and reflects countless hours of Research and Development (R&D). Capitalism controls the structure of knowledge creation and incentivizes the pursuit of increasing productivity. Transnational industries appropriate new knowledge through favorable circumstances and social structures, which result in increased social inequalities and surplus transfer to central economies.

In addition, many of the new products come with an elevated price tag because their production is guarded by patents that prevent other companies from accessing the exclusive know-how. The restrictive conditions of access to technological benefits in sectors such as health, agriculture, and new energies impact the well-being of the inhabitants of countries located on the periphery.

As a result, market monopolies emerge, giving companies the power to set high prices without fear of competition. This is a prevalent characteristic of contemporary capitalism, with firms frequently teaming up to reduce price competition and maximize profits (Záyago Lau, 2021). High technologies like nanotechnology and artificial intelligence are incorporated into this systemic logic, leaving peripheral countries' economic and development systems in the rearview. Under capitalist development, incorporating science and technology into production is crucial for maintaining the functional integrity of the system and securing profits. Nevertheless, it can also lead to negative socioeconomic consequences that hinder social progress and well-being.

Countries such as the United States, Japan, and Germany hold the characteristics of central countries within the world system; that is, they focus on producing capital-intensive technological goods and maintaining independence regarding their R&D priorities. According to Wallerstein (2020), Core countries employ various means to exert their influence, including but not limited to military might, economic prowess, and political authority. Military power can manifest in defense alliances, military bases, and weapons technology, while economic power can include financial aid, trade agreements, and control over natural resources. Political power, on the other hand, can be wielded through diplomacy, international treaties, and membership in international organizations.

China's complex political, economic, military, and technological landscape presents a unique challenge when attempting to classify its position in the global arena within the World System Theory. China exerts significant hegemonic influence in several areas. On the political front, China's one-party state and centralized governance structure enable it to wield considerable power domestically and internationally. Economically, China's rapid modernization and growth have made it a major global trade and investment player. China's advanced technological development in artificial intelligence, nanotechnology, 5G networks, and space exploration further enhances its influence and capabilities. Despite not being a central capitalist country, it has many characteristics that can place it as such.

The semi-periphery links low-income peripheral states to high-income core states, adding stability to the world system through interaction (Wallerteind, 1976). These nations are often focused on the manufacturing and exportation of industrial goods and commodities. Mexico, Brazil, Argentina, India, Indonesia, South Korea, Singapore, and Turkey have this function within the world system. While technological and economic development and political dominance separate the semi-periphery from the periphery, they need more power and economic dominance to acquire the function of core nations, and they still have much-unmanaged poverty and socioeconomic instability, placing them beneath the core (Wallerstein, 1974).

Peripheral countries remain underdeveloped for various reasons. One crucial factor is the need for more technological development (Wallerstein, 1976). Countries on the periphery are highly dependent on technological advances from the center but also maintain exports of raw materials and minerals to the central countries. They can also suffer from political instability and have no significant economic influence in the global system. Examples include South Africa, Egypt, the Philippines, Malaysia, and Vietnam (the latter on its way to enter the semi-periphery).

Within this analytical framework, we advance the study of the convergence between nanotechnology and artificial intelligence and its impact on strategic sectors for the (under)development of peripheral countries.

2. An Overview of Nanotechnology Development

No economic sector is exempt from incorporating nanotechnology in its production processes nor a wide variety of products distributed in global markets (Villa Vazquez, 2022). Nanotechnology, which involves the manipulation of matter at the 'nano' scale, is a necessary enabling technology that takes advantage of the different quantum physical capabilities of matter by creating new structures with new molecular features (NSTC, 2009). This comprises designing, characterizing, manufacturing, and controlling the shape and size of matter at the nanoscale. Nanotechnology has significantly improved chemical, physical, and biological properties, processes, and phenomena; it uses tiny particles to create new materials and technologies with unique properties (Nasrollahzadeh et al., 2019). According to Emergen Research (2023), a company dedicated to exploring the growth of high-tech markets, the global nanotechnology market valuation is expected to reach USD 290.93 billion in 2028. The promise of profits and market competitiveness through nano innovation has endorsed the creation of several national nanotechnology initiatives or special funding programs worldwide.

The United States, China, South Korea, and Japan top the list at the international level. These countries are characterized by developing specific initiatives in R&D in this area; the United States allocates close to USD 2 billion annually to finance nanotechnology projects, while the Korean brand Samsung assigns more than 500 people to the development of R&D on nanotechnology (Gutiérrez, 2015). These countries are central to global nanotechnology research and development control of this enabling technology.

The world's leading National Nanotechnology Initiative is that of the United States of America (USA). The early promotion of nanotechnology development through the National Nanotechnology Initiative (2001) has contributed to the USA's leadership in patenting (NNI) (Sargent, 2014). Since its inception, the NNI has been the instrument of the US government to direct the trajectory of nanotechnology. By 2024, the investment accumulated was $40.7 billion, distributed among various agencies (in descending order - USD million dollars): the Department of Health and Human Services (HHS), ($2.457); the National Science Foundation (NSF), ($620); the Department of Energy, (DoE) ($377); Department of Defense (DoD), ($218) and the Department of Agriculture (DoA), ($23.4) (NNI, 2024). According to the U.S. Bureau of Labor Statistics, in 2012, there were 1,365 companies with 19,400 workers, while by 2022, there were 2.660 with 27,890 workers, generating profits of USD 4.55 billion and 20.8 billion, respectively (TPG, 2023). It's important to note that private nanotechnology companies in the US keep their exact profits private, which leads to some inaccuracy in overall calculations. However, from 2002 to 2022, their earnings are estimated to be between 928 billion and 1.1 trillion dollars (TPG, 2023). The USA still leads the global nanotechnology market regarding "nano products".

In China, according to Siddiki (2022), the government has recognized the potential of nanotechnology as a pivotal technology within China's 13th Five-Year Plan. The strategic move is geared towards enhancing competitiveness and has reaffirmed state funding alongside legislative and regulatory backing. As part of the ambitious 'Made in China 2025' initiative, nanoscience and nanotechnology R&D is crucial to China's vision of becoming a leading high-tech manufacturing powerhouse (Siddiki, 2022). From a geo-economic and geo-strategic point of view, China has developed a strategy of competition against the USA based, among other things, on the control of high-tech and innovation fields. This, of course, includes nanotechnology. In China, the National Committee for Nanoscience and Nanotechnology is the governmental body overseeing nanotechnology development in the country. Other agencies indirectly participate in this effort, such as the Chinese Academy of Science, the Ministry of Science and Technology, the Ministry of Industry and Information Technology, and the Ministry of Education. The Chinese government has built "Nanopolis," the world's largest nanotechnology industrial zone. It covers 300 square kilometers in the eastern city of Suzhou. China and Singapore have collaborated as partners since 1994 to establish this industrial park. Nanopolis became part of the National High Technology Research and Development Program. Specifically, initiative 863 was launched by Den Xiaoping in 1986 (Borras, 2023).

South Korea and Japan are at the forefront of nanotechnology development, competing for second and third place globally. These countries have leading companies incorporating nanotechnology into their products, including semiconductors, computers, robotics, and information technologies. Both countries have been protagonists in the transition from microelectromechanical (MEMS) to nanoelectromechanical (NEMS) systems.

Since the early 2000s, South Korea has promoted the development of nanotechnology. However, the Act on the Promotion of Nanotechnology, published in January 2018, provided the framework to articulate the collaboration of several agencies, ministries, universities, and companies to "contribute to innovations in science and technology and the development of the national economy, by creating nanotechnology research infrastructure and promoting the systematic fostering and development of nanotechnology" (KLRI, 2018, p1). There are approximately 150 nanotechnology companies in South Korea, with Samsung and the Korea Advanced Institute of Science & Technology (KAIST) having over 2,000 and 150 patents, respectively (WIPO, 2020).

Even though Japan's dominance in the electronics and nano components industry is in the past. It has, however, become a significant player in manufacturing new materials, bringing to light inventions like Neodymium magnets, lithium-ion batteries, blue LEDs, photocatalysts, and carbon fibers. The nanosensor industry is an area of special interest for Japan. In 2023, in an article published by Nature Research, it was announced that the Japanese chemical company Mitsui Chemicals, Inc., created a device that employs functional polymers to monitor for trace quantities of multiple target gases rapidly. Switching the polymers used allows the device to be readily adapted for sensing applications, ranging from quality control in food and beverage production and chemical processes to non-invasive diagnosis of multiple health conditions through breath analysis (NatureResearch, 2023).

The number of companies, products, and patents derives from an important support in nanoscience, evidenced by the number of scientific publications on the subject. The world leaders are China, the USA, India, Germany, Japan, and South Korea.

Table 1. Number of nanotechnology-related publications (articles) by country as of 2023 (Web of Science – WoS)

Country	*Number of articles (thousand)*	*Ranking*
China	938.217	1
USA	437.679	2
India	211.443	3
Germany	157.146	4
Japan	152.723	5
South Korea	151.804	6

Source: Own design with data from Statnano (2023a)

Patents are a way to demonstrate a country's centrality in formalizing and claiming ownership of nanotechnology-related knowledge. One of the most important intellectual property offices in terms of the privatization and commercialization of knowledge worldwide is the United States Patent and Trademark Office (USPTO). Most companies aim to register their inventions in this office as it covers the world's largest market.

Table 2. Number of nanotechnology patents (granted) – by country of origin of inventor as of 2023 (USPTO)

Country of origin of applicant	*Number of patents (Thousand)*	*Ranking*
USA	69.100	1
Japan	11.440	2
South Korea	11.224	3
Taiwan	7.305	4
China	7.032	5

Source: Own design with data from Statnano (2023b)

Table 2 illustrates how the USA, Japan and South Korea lead the way in manufacturing nanotechnology products. Although China has surpassed the USA in scientific publications, the USA maintains the competitive edge in both intellectual property in nanotechnology development and the commercialization of nano products.

It is worth noting that peripheral countries have also participated in developing nanotechnology. However, they have done so under less advantageous conditions than the countries in the center. Some excel in scientific research, while others focus on training qualified personnel or strengthening their nanotechnology laboratories. Nonetheless, they fall behind central countries regarding scientific publications, patents, companies, and products.

In Latin America, Brazil, Mexico, and Argentina are the leading countries regarding publications, patents, companies, and infrastructure (Foladori et al., 2018; ReLANS, 2024). Egypt is currently the leading country in the African continent regarding nanotechnology research. Meanwhile, South Africa has filed the most patents and established the most nanotechnology companies and institutions (Konde et al., 2020). In Southeast Asia, Singapore stands out, followed by Malaysia, Vietnam, Indonesia, and the Philippines (Statsnano, 2023a). Overall, countries in Latin America, Southeast Asia, and Africa are home to numerous nanotechnology publications and some companies. We have provided an overview of some data regarding this matter in Table 3.

Table 3. Nano Publications and Companies by Country (Latin America, Southeast Asia and Africa) (As of 2023)

Country	*Number of nano / publications (WoS) (Thousand)*	*Companies*
Brazil	45.760	1085
Turkey	38.585	46
Singapore	38.354	51
Egypt	36.893	4
Malaysia	28.273	79
Mexico	20.945	138
South Africa	13.441	16
Vietnam	12.288	15
Argentina	9.808	43
Indonesia	6.201	19
Philippines	1.096	7

Source: Own design with data from ReLANS (2024); Statnano (2023b); Barbosa, Invernizzi & Bagattolli (2021); Konde et al., (2020). We include Turkey in this table as a reference.

Within this group of countries, Brazil, Egypt, Malaysia, Mexico, Singapore, and Turkey are the top countries publishing nanotechnology research. By the end of 2023, they had published over 20,000 papers in journals indexed in the WoS. Brazil, Mexico, Malaysia, and Singapore have the highest number of companies producing and selling nano-enabled products. However, most countries in these regions still need to catch up to the leading nations in nanotechnology (countries at the center). Only a few of these peripheral countries have established clear national strategies to steer the growth of this sector. Therefore, they must implement policies to endorse nanotechnology development while aligning their objectives with each country's industrial and socio-economic priorities. That is the primary obstacle within the center–periphery-dependent economic structure.

3. Nanosensors: The convergence of Artificial Intelligence (AI) and Nanotechnology

In general terms, AI is the process of developing machines capable of replicating human intelligence to solve different tasks. Such tasks include problem-solving, perception, speech recognition, decision-making, planning, and learning. In 1950, Alan Turing was one of the pioneers in reflecting upon the notion of machines being able to think and act upon their thinking. His famous paper "Computing Machinery and Intelligence" is still a reference source for analyzing and discussing the possibility of machines becoming intelligent (Turing, 2012).

In today's world, there are three kinds of AI depending on capabilities and outreach, according to the corporation IBM (2023) these are:

> 1) *Artificial Narrow AI*. It is the only type of AI that exists today. Any other form of AI is theoretical. It can be programmed to perform a single or narrow task, often far faster and better than a human mind can. However, it can only perform within its defined task. The "smart assistants" such as Alexa, Siri, and Watson are some examples.
>
> 2) *Artificial General Intelligence (AGI),* or Strong AI, remains hypothetical. The goal is to develop a machine that can acquire knowledge and abilities through previous experiences and apply them to solve novel challenges in various settings without requiring human instruction.
>
> 3) *Artificial Superintelligence*, or Super AI, remains a highly sophisticated concept that has yet to become a reality. If achieved, Super AI will possess cognitive abilities beyond human beings, allowing it to think, reason, learn, and make judgments.

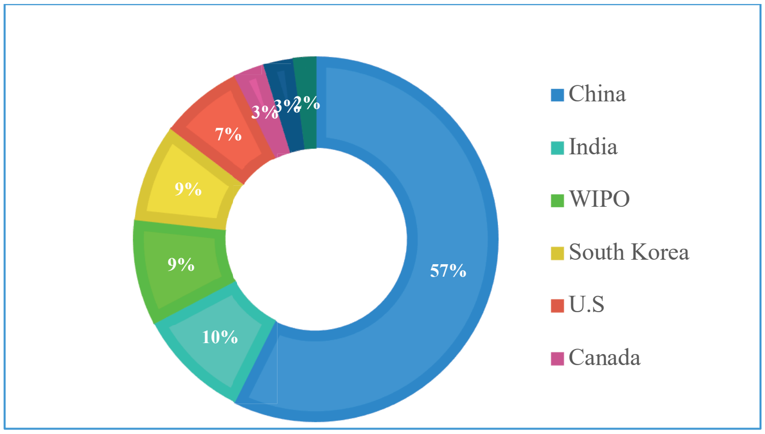
The convergence of nanotechnology and artificial intelligence involved the miniaturization of electromechanical devices. And the development of the Industry 4.0 was the narrative space where this materialized. Thanks to their advanced capabilities and compact size, nanosensors and nanoactuators have become indispensable components of Industry 4.0. This "4.0 era" is not simply a technological revolution that transforms energy sources, introduces new technologies, or revolutionizes how we manipulate matter. Instead, it implies a confluence of different technologies, with nanotechnologies playing a crucial role alongside ICT and the industrial internet. Since the second decade of this century, nanotechnology has been the bridge to interconnect several technologies (big data, cloud, Internet of Things, G5, and others), all part of what is known as Industry 4.0; this does not mean that nanotechnology has been displaced; on the contrary, all these chained technologies have nanotechnological components, and Industry 4.0 was conceivable from them (Foladori & Ortiz-Espinoza, 2021).

MEMS and NEMS are compact devices incorporating electronic, mechanical, and electrical components. Their size can range from a few tenths of a micrometer to several millimeters or some nanometers, and they can interact with physical, chemical, and biological processes at the microscopic level (Zarepour et al., 2014). These systems can detect or manipulate specific physical parameters at the microscale and even generate detectable effects on a larger scale. NEMS, specifically, are devices that measure less than 100 nanometers and can leverage the unique physicochemical properties of materials at this scale.

Numerical simulations can be constructive when analyzing experimental results at the nanometer scale. For instance, according to Torres-Solis, C., and Quiroz-Juárez (2023), creating analytical approximations can be complex. Machine learning algorithms have gained more popularity in recent years due to their effectiveness. These AI-based algorithms can accurately estimate predefined models from data. Additionally, machine learning techniques can help researchers understand the relationship between output and input data, allowing them to map controllable physical variables like temperature, pressure, and volume to the functional properties of a nanomaterial. NEMS capture physical movements and chemical and biological changes, encode, store, send, and receive feedback. Through this arrangement and handling of information, nanosensors become a reality. Nanosensors form the initial information node known as nanonodes. These nanonodes are further scaled up to form nano routers with more excellent information storage and processing capacity. The nano routers then connect to more complex nodes known as interfaces, which act as gateways to the nanosensor networks and enable communication with the outside world (Foladori & Ortiz-Espinoza, 2021; Critchley, 2019; Piro et al., 2013).

The continuous evolution and miniaturization of nanotechnology have dramatically influenced our capacity to handle and manage vast quantities of data and efficiently transmit it over long distances. AI algorithms undeniably play a crucial part in this process. However, it is the hardware that ultimately drives them. With powerful nanoprocessors and memory, it is now feasible to create computing systems ranging from hundreds to millions of units, such as supercomputers, housed in cutting-edge data processing centers. Undeniably, nanosensors are a product of the electronics industry but work with biological, chemical, and physical signals. That is why they are used in all economic sectors. Due to its geo-economic importance, developed or central countries dominate AI and nanotechnology investment in both R&D and patents.

Fig. 1 Nanotechnology and artificial intelligence patents by country untill 2023 (Patentscope)



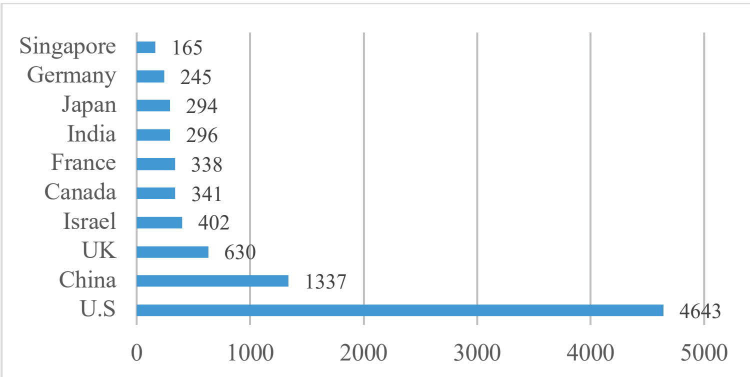
Source: Own design from Ortiz-Espinoza, (2023) with data from Patentscope, Wipo.

Regarding converging patents between nanotechnology and artificial intelligence, China is the main applicant, according to WIPO's Patentscope, followed by India and the USA (Ortiz-Espinoza, 2023). There is very little presence of peripheral countries.

There are a very wide number of economic sectors or areas that use nanosensors. According to Javaid et al., (2021, p.7), nanosensing capabilities can be applied to track water, soil and environmental changes, identify tiny particles in agricultural fields, detect infections to avoid water contamination, check micronutrients and water contents, recover precise health data, detect particular gases in the environment, detect human psychological data, monitor biological cells, smart tracking and tracing, among many other applications. Nanosensors have applications in healthcare, defense and military, environment, food, and agriculture, and the market size will reach the 106 billion mark in 2027

(Technavio, 2024). The promise of profits is important, which is why several AI start-ups are in central countries, as shown in the next figure.

Fig. 2 Number of AI startups by country (2012-2023)



Source: Own design from AI-index – Stanford University (2023)

Nanosensors are feasible thanks to NEMS. NEMS interconnects with AI to gather, analyze and provide feedback on specific data. While China dominates in nanosensor patents, the USA leads in investment towards new companies. These data indicate that the peripheral countries are not participating in R&D or patent development. The convergence between AI and nanotechnology represents an affront to the development of peripheral countries. It is a race that peripheral countries are losing, and the distance between them and central nations is becoming unattainable, which may mark a gap of no return in the endless extension of the underdevelopment of peripheral countries.

It is essential to mention that other social implications related to the convergence between nanotechnology and AI should be addressed but go beyond the space limit of the paper, such as Job displacement through automatization of processes and displacement of skills; concentration of political power derived from the accumulation of capital of the owners of these technologies; discriminatory practices due to social class, ethnical profile, or origin; transparency and accountability of specific algorithms; privacy concerns of data handling; among others.

Conclusions

In the second decade of this century, nanotechnology´s dynamic properties have allowed sensors to acquire sizes below 10 nanometers and be incorporated into NEMS and applied to all economic sectors. The technical execution of nanosensors is realized from sophisticated processors of great capacity, all at the nanoscale and possible thanks to nanotechnology.

A comprehensive understanding of the underlying factors is required to analyze the intricate relationship between center, periphery, and semi-periphery countries and their respective technological advancements. Typically, developed nations occupying the center have established themselves as pioneers in innovation, particularly in advanced fields such as nanotechnology and artificial intelligence, where they excel. This is mainly due to their superior technological foundation, which has enabled them to maintain their dominant position in various aspects, such as publications, patents, investments, and company creation.

In contrast, developing and emerging economies, often found in periphery and semi-periphery countries, need to catch up with advancements. This has led to a significant technological divide between developed and developing nations. This disparity is primarily related to economic development, education, and infrastructure. Developed nations have invested heavily in research and development, education, and infrastructure, which has allowed them to create a conducive environment for innovation. On the other hand, developing and emerging economies face several challenges, such as inadequate infrastructure, limited access to education, and insufficient research and development funding.

The central countries have significant influence and control over advancing nanotechnology and artificial intelligence. The combination of these two technologies, which has materialized in nanosensors, is proving to be a significant obstacle for peripheral countries to achieve industrialization, maintain economic independence, and promote technological development to match their national priorities. The problem requires a well-organized strategy that requires a sustained effort for a significant amount of time to modify the structures and the center-periphery economic relations. Technological advances of new technologies increasingly involve leaps in knowledge, patents, products, and market share, which the peripheral countries are crawling due to the hegemonic social relations of technological development.

From the subjective social analysis, nanosensors can cause a shift in the job market, which may result in an increasing demand for roles requiring creativity, critical thinking, and problem-solving. On the other hand, from the objective form of social analysis, nanosensors, as they amplify their presence in the market under the hands of transnational corporations, will increase economic and social inequality.

Collaboration among policymakers, technologists, ethicists, and the broader society is necessary to address the social implications of nano and AI integration. However, it is also essential to acknowledge that social relations of technology development under capitalism play an important role in stopping semi-peripheral and peripheral countries from benefiting from these technologies.

Bridging the technological gap between central and periphery/semi-periphery countries requires concerted efforts from governments, businesses, and civil society. These efforts should foster inclusive and sustainable development to help these countries reach their full potential.

To achieve this goal, governments of the periphery and semi-periphery should prioritize investments in education and training programs to equip their citizens with the necessary skills and knowledge to create a national system of innovation aligned with nationwide priorities. They should also create a supportive regulatory framework encouraging investment and endemic innovation.

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