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Contents

An Overview of International Order and Its Impact on International Political Economy

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Abstract; In the existing literature on international relations in the country, realism and the theoretical branches associated with this school enjoy high acceptance. Various factors have driven the country's elites towards a specific reading of realism. The author proceeds from the belief that realism encompasses a diverse set of different theories.

The lack of complete knowledge of this set, the efforts and the inability to accurately understand the key concepts in this field, will lead to a superficial and inaccurate perception. The present study aims to address this deficiency with a new perspective and, if possible, provide an answer. With this description, the question that the present study attempts to answer is: What capacity does realism have to respond to today's new issues in the field of changes in the international system? In response to this question, it can be said that Robert Gilpin's reading of realism based on the cycle of hegemony (in international politics) alongside hegemonic stability (in international political economy) provides a suitable window for presenting a more or less narrative account of this issue (the transformation of the international political economy system).

In this regard, the Solow economic model, which is used to strengthen, enrich, and attempt to quantify Gilpin's reading of realism, provides a framework for providing a better explanation of the transitions and changes in the system. The writing strategy of the previous paper is of the comparative type, and its research method is also of the basic, case-based, and static type.

What has been examined in this study is the use of Robert Gilpin's theories in the fields of international politics and international political economy, which have been strengthened and enriched by Robert Solow's economic model to better explain the cycles and changes in the international political economy system.

Keywords: Realism, Hegemonic Stability, International Political Economy, Economic Hegemony, Changes in the International System

1. INTRODUCTION

In the international relations literature in the country, realism and the theoretical branches associated with this school enjoy high popularity and acceptance. In addition to these matters, various factors have driven the country's decision-making and scientific elites towards a specific reading of realism. This author believes that realism encompasses a diverse set of different theories (of course with common foundations and assumptions), and that a lack of complete familiarity with this set of efforts and an inability to accurately understand key concepts in this field will lead to a superficial and inaccurate perception. This reading, which is mostly inspired by the theory of the Waltz-like Pradzani, has taken on a more abstract form in today's conditions and does not enjoy much popularity compared to the current literature in the current international system.

The reliance of today's realist analyses in Iran is based on a distribution of power that, although it will be helpful in some issues; But it is certainly not an adequate answer to the current problems of the international system; therefore, further research is on the way to providing a new reading of Robert Gilpin's theory.

To put it more clearly, contrary to what is common in Iran, the current realist literature does not rely solely on security, military, and rigid power distribution issues among the players. After the collapse of the Soviet Union at the end of the twentieth century, the realist elites clearly felt the need to move away from the harsh military issues in order to survive this school.

However, this move does not mean forgetting and going beyond Waltz realism; But the maturity of this school is fully evident (it should be noted that these efforts in realist literature did not occur only after the war, and the efforts of theorists such as Buzan and Gilpin were noticeable even during the Cold War). For example, the movement of analyses and ideas from security and military issues towards other issues such as political, economic and social issues is evidence of this claim. Among the aforementioned areas, it can be safely said that, in view of the economic and oil crises of the 1970s, which economic thinkers and international relations alone were unable to explain, the expansion of globalization, the expansion of economic relations between countries, the growth of international players such as international organizations and multinational corporations in the international economy, the need to pay attention to issues of international political economy. It was felt more than before.

What seems to be of great importance is moving away from simple and evolving narratives in the analysis of international relations and politics in scientific and academic circles and rejecting rigid and one-dimensional views of realism in developing Islamic countries, especially in the field of security and military issues.

This study has attempted to show that the concept of realism is not a purely abstract one from the perspective of the balance of power, and that different conceptions of this school are possible. Another goal of this research is to move away from abstract analyses, which are not widely accepted in modern realist literature, and to integrate analyses by using economic and political economy issues.

The question that this study seeks to answer is:

What is the capacity of realism to respond to the new issues of today in the field of changes in the international system? It is necessary to mention at the outset that in examining this fundamental issue, several questions can be raised and considered. The present author, emphasizing one important aspect of this, is the transformation in the system of organized international political economy.

In response to this question, it can be said that Robert Gilpin's reading of realism based on the cycle of hegemony (in international politics) alongside hegemonic stability (in international political economy) provides a suitable window for presenting a relatively realistic narrative of this topic (the transformation of the international political economy system).

Although Gilpin's theories provide the necessary background for this situation, his theory also has limitations. In this regard, Solow's economic model, which is used to strengthen, enrich, and attempt to quantify Gilpin's reading of realism, provides the basis for a better explanation of transitions and changes in the system. In this field of knowledge (hegemony in international politics), thinkers such as Charles Kindleberger, Antonio Gramsci, and Robert Gilpin have contributed to this field.

However, among the thinkers mentioned, Robert Gilpin is of ambivalent importance because he has discussed international political economy alongside international politics. In this regard, it seems necessary

to refer to two important books by this scholar of international relations, namely War and Change in World Politics (1981) and World Political Economy (2001).

In the first book, he examines the debates on hegemony and the types of change in international politics, and in the second book, he examines the debates on international political economy with a view to the stability of hegemony.

Another important work on the transfer of power between great powers is the book The Inevitable War (2017) by Graham Allison. In this book, Allison, using the theoretical framework of Tosi did, examines the behavior of great powers and the way power is transferred between them. The present study, by adopting the assumptions of the scientific-empirical approach, aims to present a new reading of Robert Gilpin's theories through economic theories. The strategy of this study is comparative and the type of research of this study is also a basic, case study and static.

The present study is based on five main sections, the first of which is devoted to the criticism and examination of the views of the dominant current in the literature of international relations in Iran. In the second section, the capacities of the Gilpin model in the fields of international politics and international political economy are explained in comparison with other schools of thought.

The third section is also dedicated to introducing Robert Solow's model in economics, which is placed next to Gilpin's model in the fourth section to provide a new theoretical framework for explaining international political economic issues. In this paper, the conclusion is presented in the fifth section.

2. TWO DIFFERENT READINGS OF REALISM

Different readings of realism can be categorized in various ways. One way to identify the different types of realism is to focus on the economic variable and the way different theories view the role of this variable. On this basis, two completely different perceptions can be observed within the readings of realism. These two views can be considered, with tolerance, the views of Waltz and Gilpin. This method of grouping is important because of the importance each of these readings gives to the variable economy and how much attention they have paid to changes in the international order. In the first group, the economy is important because it provides the war needs of countries; In other words, the economy (along with other effective components) is relevant because it provides countries with the ability to fight and creates a balance internally against competitors (Waltz, 1979: 118).

Waltz's neorealists, because they are overly focused on military goals, often pursue goals in the short term and allow a focus on the economy to the extent that it is necessary. Security risks are not considered. (Brooks, 1997: 446-452)

By institutionalizing the assumption in the minds of decision-makers that potential threats from competitors can be implemented at any moment, all focus and possibilities are focused solely on neutralizing threats; without long-term planning for international cooperation.

In contrast, Gilpinian realists believe that economics alone has the necessary originality; of course, this does not mean that they give secondary importance to military issues; rather, they consider economics to be a part of security and military issues and are interested in examining the interaction of economics and politics with each other (Gilpin, 1981: 67). They also focus on long-term goals and believe in the role of Factors such as technology, geography, and economic pressures influence the behavior of players. (Brooks, 1997: 456-459)

This spectrum, with the aim of a subtle understanding of the issues of the international system, returns to a reading of realism that was forgotten after World War II, and this has been achieved by creating a connection

between international economics and international politics. (Gilpin, 1987:12). By emphasizing the variable of science and technology and explaining its role in the domestic and foreign policy of players on the fringes of the international economy, Gilpin provided a coherent response to his own daily explanatory needs.

By raising the issue of the "technological divide" between the United States, the Soviet Union, and the European countries that were considered the great powers of the international system at that time, he addressed the question of the root of the differences in The capabilities of these countries answered. (Guzzini, 2013: 152)

If this question is asked of Waltz, he would attribute the root to the distribution of capabilities among the players; but he does not explain the origin of this distribution of capabilities clearly. In contrast, Gilpin, by directly introducing economic and technological variables into his discussions, sees the root of the power imbalance at the level of the international system in these two cases and, of course, other indirect factors. Of course, it seeks less influence than the previous two (industry, domestic politics and social groups).

Gilpin believes that power, the nation-state and the market economy are not possible without understanding the economic foundations and independently. The emergence of the international market-based economy had a significant impact on the security of states; because before the emergence of the international market economy, an independent space between the state and society existed in the areas of Political goals and dynamics existed; but with the emergence of the merchant class within societies and their competition for power and wealth, society and the state took a new direction in modernizing their organization in important dimensions of human life (including foreign policy). Of course, in the shadow of these changes, human innovation and technology accelerated.

For example, the modern army and modern weapons in the eighteenth and nineteenth centuries They were created to protect the international trading system and guarantee British property rights, and in return, merchants and investors invested in various sectors of their country, including the military, to maintain this privilege.

In his studies, Gilpin pursues the dynamics and organization of power. He is interested in understanding the factors that provide sources of power for a player to It can then explain how the hierarchy of power changes. In this regard, Gilpin organizes his research program around three axes:

1 The forces driving the change in power include the level of power of players in the international system, the players' efforts to acquire power and wealth, market mechanisms, and the players' level of technology.

2. Domestic Responses to Conflicts By introducing the concept of welfare states and valuing players who are democratic, Gilpin groups them at a higher level than other players due to their high capacity for stability against external shocks.

3. International management in power transitions, paying attention to situations of decline of great powers where risky competitions take place that led to the escalation and entry into wars based on modern technologies or other wars (Guzzini, 2013: 153-159).

Although Gilpin's reading is more nuanced due to its attention to the role of institutions and internal bureaucracies of countries, the ideology and prestige of countries, technology and more importantly Of all the international economics literatures, Waltz's readings are richer; however, Waltz's views were more widely accepted than Gilpin's for three reasons. These reasons are:

.1 The deadlock of the Cold War and the despair of international relations scholars about the international order's exit from the bipolar state (at least at that time) led to a tendency towards Waltz's views, which were

more about problem-solving than about change and transformation. In the current situation as seen in Gilpin's writings.

2. Waltz published his views at a time when social science was at the height of its behaviorist tendency. By introducing the category of structure into his theory, Waltz took an important step towards scientificizing international relations. This is while Gilpin's theory also incorporates works from the literature of the rationalist era in international relations and its reliance on history.

.3 Using the theory of international politics is much simpler than Gilpin's theory of hegemony rotation. A researcher with a mastery of the concept of structure in the international system, the balance of power, and acceptance of the assumptions of the theory of international politics (anarchy, the functioning of the same players or the same self-preservation, and the difference in the distribution of power among the players) can easily explain the conditions of the international system; however,

to use Gilpin's theory, one the researcher must pay attention to intangible ideas such as prestige, while mastering history, international economics, the functioning of domestic institutions of countries, technology, and geography. (Wohlforth, 2011: 1-3)

From what has been discussed, it is quite clear that the challenges and efforts of realists are aimed at going beyond the problems and finding answers to the questions that Waltz's theory faced after the collapse of the Soviet Union.

The collapse of the Soviet Union is not just a Waltzian perspective It not only posed a problem for the interpretation of the world, but also seriously damaged the reputation of realism in academic circles. This issue has given rise to extensive efforts within realism to overcome this challenge and has given rise to numerous reconstructions of realism.

Perhaps if realism had not been reduced to Waltz's structural theory and had provided a platform for Gilpin's argument, it might well have been explaining the events of the end of the Cold War and after it with realist theories and have not faced serious criticism to this extent. However, Gilpin's theories have received less attention than Waltz's theories.

In the following, an attempt will be made to address Gilpin's theories more. In view of these issues, an attempt will be made to summarize Gilpin's theory of change in international politics and to examine the theoretical capabilities of this subject. Explanation given.

3. GILPIN AND CHANGE IN INTERNATIONAL POLITICS

It seems essential for any interpretation of Gilpin's argument to consider both aspects of his theory, namely hegemonic stability and hegemonic rotation. It is clear that Gilpin's view of change in international politics rests on two fundamental pillars, and this paper has attempted to address these two important issues.

3.1 The Hegemonic Cycle

Given that this section is based on Gilpin's thought, it seems necessary to first state his assumptions about realism and the international system. Gilpin bases his interpretation of political realism on three assumptions.

1: The fundamentally contradictory nature of international affairs.

2: The essence of social reality is the group, which in contemporary times means the nation.

3 The advance of security and power in all dimensions of political life and human motivations. (Gilpin, 1984: 304)

By focusing on the rise and fall of hegemons and great powers, Gilpin is presenting a statement from the realist literature in which change and transformation in the international system is the focal point.

Gilpin imagines a hegemon in a state where there is no rival or competitor to challenge its will in various arenas and where it is at the forefront of economic, technological, and industrial capabilities among the players in the international system.

This hegemon is interested in expanding its interests in various political, economic, and even territorial aspects. As long as the hegemon can afford the costs of its expansion, it will not stop expanding its will; but as soon as the costs of expansion and the ability to afford the costs become equal, this process will stop. (Richardson, 1991: 72)

In addition, the power of one or more players may reach a level where they endanger the interests and legitimacy of the dominant power and take steps to maximize their own interests; That is, when a player or a group of players are dissatisfied with the distribution of benefits from the existing system, have the necessary capabilities and resources to confront the hegemonic power, and also have the necessary will to change the system, there is a possibility of system change. Gilpin believes that the decline of a hegemon endangers the international system; in other words, the decline of a hegemon means the collapse of the three pillars of the international system.

1: Hegemonic power or powers that are capable of governing and enforcing laws.

2: A set of common economic, political, and security interests that are intertwined.

3. It destroys the shared ideological commitment to the values on which the system is based. (Spiezio, 1990: 167-170)

According to Gilpin, the dynamics of the international system have been profoundly transformed by the mutual feeding of the growth of the world market economy and the emergence of territorial states. In the current context, Gilpin sees two elements of change: first, technological changes that increase the benefits of voluntary development for the powers that be and reduce costs; Second, the different rates of growth of states provide the opportunity for discontented players to expand. (Gilpin, 1981: 14)

It is in these conditions that players begin to assess the extent to which they have the ability to challenge the hegemony that dominates the international system and order, and then how much the benefits will be if either of the two changes. The logic that governs this assessment is the logic of "cost-benefit"; therefore, creating a change in the system or international order is conditional on the existence of the two elements mentioned at the beginning of this section, in addition to the existence of the motivation to obtain greater benefits through the logic of cost-benefit.

Gilpin categorizes change into three distinct domains:

1. Systemic change: 1 This type of change occurs through profound transformations in the nature of the international system, such as changes in the nature of the main players or salient features of the international system.

In addition to the above, regime change is mainly related to issues such as profound economic, technological, productivity and sustainability changes in various models of political organization.

2. Systemic change 2 (regime change): If we define regime here as the pattern of power distribution among the players in the international system, this type of change can be assessed in terms of internal changes in the system.

These changes include such things as: changes in the international distribution of power, changes in the hierarchy of prestige and rights and the rules governing the system. This type of change is more concerned with the rise and fall of powers that dominate the international system. The change in the rules is also due to the fact that by changing the pattern of power distribution, the dominant player imposes his desired patterns and rules of interaction on other players to maximize his interests.

3. Interactional changes: 3 This type of change also refers to the change in the rules and behavioral patterns among players at the level of the international system.

Unlike the previous two changes, this type of change is very common at the level of the international system and is subject to change and transformation due to various circumstances. This type of change may be pursued by other players with the aim of creating fundamental changes. The scope of this type of change is very limited and, if it occurs, it will not lead to changes in other resources; However, in the event of a regime change, this type of change will be accompanied by a systematic change. (Gilpin, 1981: 41-44)

In general, Gilpin outlines the hegemonic cycle in three stages.

1: The idea of hegemony: the emergence of a hegemon, the creation of an international order, and the provision of public goods provision infrastructures at the level of the international system in order to maintain the legitimacy and continuity of the established order.

2. The idea of disorganization: The need to provide free rides to players in the international system to maintain the legitimacy and effectiveness of the international order has been created, which will ultimately weaken the relative power position of the hegemon.

3. The idea of decline: the decline of the hegemon, through the disappearance of the dominant order and ultimately the elimination of the public good provided by the hegemon. (Guzzini, 2013: 166)

At this stage, the question arises as to within what framework the study of international political economy can be conducted.

Can Waltz's theory of the balance of power be extended to the balance of economic power in today's conditions and issues be studied and examined within this framework? Or, given the transitional conditions and changes that the international order is facing, does another framework seem desirable? Efforts are ongoing to further test the theoretical potential of Gilpin in the field of international political economy with the help of economic models.

3.2. Hegemonic Stability

The condition for the progress of any nation-state is stability and the implicit certainty of the absence of sudden events. This rule can be considered valid in all dimensions of human life, especially in international relations and international political economy.

Many thinkers, especially realists, have stopped at the concept of peace; Although this may seem sufficient for international politics, it is not sufficient in the field of international political economy.

It is in the shadow of stability that human progress, especially in the social sphere, continues. It is possible to give a material definition of peace, which in its simplest form means the absence of war; but this cannot be done for stability.

Stability has a more international and relative meaning. Stability can be defined as the psychological stability of a group of components (human society or a group of states, international organizations) in the area of its own specific primary needs. In other words, every society has primary needs that, if met, can be said to be stable; for example, it is possible to stabilize society "A" by cutting off the Internet. Exit; if this event is not considered a very important event in society "B".

Without stability, no investment, including individuals, companies, and even governments, will risk their capital. As a result, development will not occur, because investors prefer to use their capital in areas with less uncertainty.

With this introduction, stability will be considered from the perspective of mainstream theories. We examine international relations with the aim of applying it to international political economy.

3.2.1. Stability in international political economy from the perspective of realism

The uncertainty arising from the anarchy prevailing in the international system drives countries towards self-help. This phenomenon, which well describes the logic of the behavior of great powers in the 18th and 19th centuries, is today faced with challenges, especially in The field of international political economy is facing. Although some consider the specific conditions of anarchy that currently prevail at the level of the international system to be the most desirable and refer to it as "mature anarchy" and contrast this type of anarchy with "immature anarchy". (Buzan, 2016: 148)

In immature anarchy, players do not claim legitimacy for others and only They consider the achievement of their goals to be achieved by force. None of the units adhere to their agreements, and the principle of maintaining peace in this situation will be among the ruling players. An example of this type of anarchy can be seen in times of armed peace, before the First World War.

In contrast, players in a state of mature anarchy, knowing the costs of tension and instability, seek a way to achieve their goals while maintaining Their own identity and legitimacy are beyond the acceptance of the legitimacy of other players.

In this case, the players have achieved an internal coherence and stability and are in the process of transferring it to the international environment. It is obvious that the instability of one or more of the units also affects the stability of the others.

As mentioned above, the theorists of this spectrum, who are mostly realists, shed light on the state of development and the international economy has not taken a position as a stage after the achieved stability.

However, the belief of the theorists of this spectrum is based on the argument that in the shadow of the stability created by mature anarchy, progress and development within countries are facilitated accordingly in the world economy, and in the event of a breakdown of this pattern and a return to immature anarchy, all processes of global growth and development will face disruption. (Milner, 1998)

In other words, if we consider stability and security (whether domestic or international) as a necessary condition for economic development and progress, this will be achieved in conditions of mature anarchy.

As mentioned, stability resulting from the balance of power between units in mature anarchy will provide the desired conditions; however, what should be considered is the distinction between economic stability and security stability. To put it more clearly, the realist view of anarchy can be a response to political stability, but not to economic stability. A clear example of this claim is the economic crises of the modern era.

The economic crises of the 1970s, 1930s, and 2008 all occurred in conditions where security and military stability were established through the balance of power, and this stability did not prevent economic crises from occurring. What is important is that it is necessary to distinguish between economic stability and security and political stability. Political and security stability is the foundation and foundation of economic stability; however, these two (security-political stability and economic stability) should not be considered one.

3.2.2 Stability from the Perspective of Neoliberalism

On the other side, neoliberal international relations thinkers believe that in the current situation, the degree of autonomy has been reduced due to the expansion of economic interdependence between countries, and international institutions play a very positive role in this.

This group believes that the benefits derived from cooperation between players are so high that players will not sacrifice the long-term benefits derived from cooperation for their own short-term benefits. Meanwhile, international institutions will be the link between players and a factor ensuring the benefits of both parties in cooperation, and the role of military force in the equations will be reduced (Kuhan and Nye: 2021,41; Griffiths et al. (2019: 167-171). In summary, this spectrum, the benefits of cooperation and the guarantee of the continuation of this cooperation through international institutions as a factor of stability at the level of the international system. They introduce and introduce this key phrase against the balance of power between great powers in anarchic conditions.

There is no doubt that neoliberalism has acted much more strongly than neorealists in the debate on international political economy.

This group has also produced rich literature on international political economy with regard to non-state actors, including international institutions and multinational corporations. However, there are also criticisms of this view.

Neoliberals currently present interdependence as a factor of stability without considering its consequences. Despite the irrevocability of this phenomenon, interdependence can also be considered a factor of tension in the future. In other words, countries acquire new tools against each other by moving away from previous relations and expanding their interactions. With the expansion of the order of business Among states, their interests may be harmed in different areas (Buzan, 2016: 132) and, by the same logic, as cooperation between actors expands in different areas, tension and conflict also spread to other areas. Another criticism is that this view, while accepting the structure, practically ignores it.

Waltz, in his book "Man, the State and War", draws on decision theory Rousseau's social theory argues that the behavior of the state in isolated conditions is very different from the conditions in which other players exist; in other words, through the determination of the structure, the behavior of states takes on a particular form that is sometimes not their desired one (Waltz 2021:185-194). To further explain this section, it can be said that by shaping the interactions between units, structural pressure is determined on the behavior of players and Units cannot act freely; the outcome of the behavior of other players affects the behavior of each player.

With increasing interactions, this structural pressure becomes more felt and may lead to the creation of structural tension. The best example for this claim is the high dependence of Germany and Britain before the First World War. This interdependence not only did not prevent war, but The creation of a structural tension between these two powers became the basis for the outbreak of war.

What has been examined so far has been the source of stability for the realization and development of international political economy from the perspective of the theories of the main stream of international relations. It is clear that due to the criticisms made (mentioned above) in the field of international political economy, these scientific currents in international relations have been effective. These theories are not sufficient to explain the issues of international political economy in the current context.

It seems that Robert Gilpin's view of stability in international political economy will answer a wider range of questions in this field than other theories on this subject.

3.2.3 Stability from Gilpin's perspective

Every theory that has been criticized and examined in the field of stability has its strengths and weaknesses. Among the existing theories, Robert Gilpin's "hegemonic stability" theory is suitable for better explaining stability in international political economy. In summary, it can be said that, according to this international relations thinker, stability in the international system will be established through the presence of a hegemon.

This hegemony, which is achieved in part through international economic and political institutions, plays a significant role in reducing the economic autonomy (self-sufficiency) of the players in the international system (Gilpin,1401:142); in other words, it is through the existence of an almost dominant power in the economic dimension of the international system that the possibility of cooperation and division of labor among the players is provided.

This power is created by Public goods, including international security, guaranteeing the absence of fraud and the return of benefits from cooperation between countries, determining the pricing mechanism, creating legal infrastructures to make players obedient, and allowing interaction in a different way in the economic dimension than in the political dimension at the level of the international system (Griffiths et al. 2019:37)

Here it is necessary to further explain the stability of the type of Hegemony in the international economy, public goods and their importance as provided by the Hegemon are mentioned. The most important public goods from the perspective of hegemonic theorists are:

.1 Creating financial and trade stability through:

A: Rediscounting mechanisms to provide liquidity during international crises.

B: The last resort in the international system.

C: Management of the international monetary system.

D: Maintaining the structure of exchange rates and creating coordination of macroeconomic policies among players.

D: Opening markets to flourish in damaged goods.

C: Creating a steady flow of international capital.

2. Redistributing income through international aid.

3. Regulating regulations for international violations such as economic sanctions in the international economy. (Guzzini, 2013: 167)

The hegemony of the provision of these public goods In particular, security will benefit more than other players.

Firstly, the hegemon will maintain its desired order by providing public goods and will impose its will on others.

Secondly, the hegemon itself will benefit the most from public goods; because the player has more economic, industrial, financial, technological power than others, and it is obvious that in such conditions where there is unequal competition, the hegemon will benefit most from increased interactions. In addition, other players can benefit from the advantages that hegemon has created for itself in the first stage.

The importance of public goods stems from the fact that only one hegemon can provide these goods in the international system, and it is clear that providing such goods under conditions where everyone has equal power would not be logical.

If A player will create these conditions. First, other players who are at the same level of ability as this player may use the created conditions to improve their own conditions. Here, a player who has taken steps to create public good at the international level beyond his ability will not be able to recover and benefit from his investments. Second, assuming a violation by one of the players, the player providing the public good will not be able to punish the wrongdoer; therefore, it seems that for the growth and development of the international economy, the existence of a hegemon is necessary to provide the necessary condition, that is, stability.

This approach has been criticized as defending the logic of US policies and taking a historical approach to issues instead of a scientific one. It is; but the reality is that a free market economy requires a hegemon to fulfill this necessary condition.

Given that there is a direct relationship between hegemony and free trade, without a hegemon, international cooperation in financial and commercial matters seems almost impossible, or at least very difficult (Gilpin 2022:142, 144).

It is clear that with the decline of the economic and political power of the hegemon, the implementation of commitments will not be guaranteed as in the past, and coercive actions by the players will replace the prestige of the hegemon, and the power of the hegemon will no longer be able to prevent the players from rebelling and challenging the legitimacy of the existing order.

In these conditions, it is possible to return to anarchic conditions and increase economic autonomy and self-sufficiency. In conditions of hegemonic weakness, players expand their power and exploit their resources and will to the extent of their own. The greater the resources and will of a country, the greater its will to expand to the point where it can replace the weakened hegemon and assume its responsibilities in providing the public goods of the international system.

The new hegemon, in the form of power, establishes its own new system and order, and through the resulting legitimacy, seeks to secure its own interests to the maximum extent. Research on this group of events falls within the field of "change studies," which deals with the categories of system change and international order through the rise and fall of great powers.

What has been examined so far has only covered the international politics section and a corner of Gilpin's views on international political economy. It is clear that providing explanations based solely on the theoretical foundations of political science and international relations will only cover a part of the dimensions of international events and processes.

On the other hand, purely economic explanations will also follow this reductionism; therefore, the economic explanation of the dimensions of change will be addressed in the continuation, so that ultimately a

theoretical framework in the field of international political economy can be provided that can adequately explain and explain the literature in the field of change in international political economy.

It is also worth mentioning that Gilpin, in his book War and Change in World Politics, has used the theory of hegemonic rotation to explain the mechanisms of hegemonic changes in international politics. On the other hand, in his books and articles on international political economy, he has also discussed the need for hegemonic stability in international economics.

What is being explored next is the combination of these two ideas of Gilpin for use in international political economy. In other words, by combining the two debates of hegemonic stability and hegemonic rotation, an attempt has been made to address the hegemonic rotation in international political economy.

Importantly, despite the strengths and richness of Gilpin's theory, there are important objections and problems with Gilpin's theory, which uses the Solow model to strengthen and enrich this approach as a small attempt to quantify and exclude the discussion from the qualitative realm so that the hegemonic cycle approach is more tangible within the framework of international political economy.

4. Solow Model in Economics

In neoclassical economics, the Solow growth model is of great importance. Although newer theories have been considered by economists over time, this model is still relevant for explaining some issues. The Solow growth model, which is used in macroeconomics, is based on two main axes: the production function and the explanation of the temporal changes in capital.

The first axis of the Solow model is the production function. This function is a combination of various production factors that ultimately gives us the amount of production. This function is defined as follows:

Equation (1) $Y = F(K, L)$

In this equation, "k" is considered as the capital variable, "L" as the labor variable, and "Y" as the production rate (of course, in this study, this component will be used under the title of the interest rate and the results obtained at the level of the international system). Since this function is a first-order homogeneous function, therefore, by multiplying the aforementioned variables by a constant number, the value of the function also increases by the same amount. That is, by multiplying "t" by the capital and labor variables, we have:

Equation (2) $F(tK, tL) = tF(K, L) = tY$

After multiplying the production function variables by a constant (t), it can be concluded that when the production function variables are equal to t, the production rate also becomes equal to.

Here, another parameter called the level of technology (A) is introduced. By adding this parameter to equation (1), we will have (Neely: 240-242: 2019)

Equation (3) $Y = F(K, AL)$

It is important to note that in the Solow model, the per capita production equations are of great importance. In this section, by dividing both sides of the Solow production function by the labor force variable (L), the per capita production equation is obtained.

By dividing both sides of equation (1) by (L), we have:

Equation (4) $\quad Y = F\,(K,\,L)$

Equation (5) $\quad \dfrac{Y}{L} = \dfrac{1}{L}\,F\,(K,\,L)$

Equation (6) $\quad \dfrac{Y}{L} = y = F\left(\dfrac{K}{L},1\right) = f(k)$

Equation (7) $\quad y = f(k)$

In the above equations, we refer to the variable "y" as per capita production. This form of the production function shows the dependence on the capital variable well (based on the Solow model).

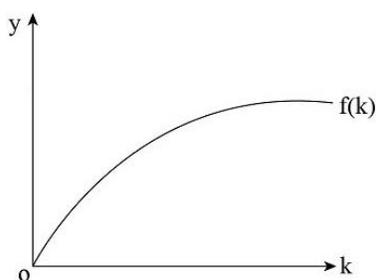The diagram drawn using the above function is as follows:

Figure 1. Production function in the Solow model (Neeli, 2019:243)

The graph above shows well the rate of change in output relative to change in capital. As capital increases, per capita output increases and vice versa. It is necessary to mention again that although this diagram is derived from equations in which the labor force variable has played an important role, this diagram is desirable due to the elimination of the effect of this variable through mathematical equations and the creation of a dependent function on the capital variable.

4.1 Capital Consumption in the Solow Model and the Flow-Stock Model

In the economy, a part of the production is consumed and a part is also stored. This amount is often invested (of course, if there are no unforeseen needs such as war, economic crises, or the bankruptcy of large financial institutions); In other words, investment can be considered as a coefficient of total production:

Equation (8) $\quad S = sY$

In this relation, "s" is the investment rate of a country and "s" is the coefficient according to which the amount of investment is calculated from the total production. Also, the capitals that a country has are subject to depreciation, which is shown as follows:

Equation (9) $\quad D = dK$

From equations (8) and (9), it can be concluded that capital changes depend on two factors: the rate of investment and the rate of depreciation of existing capital; therefore, we express capital changes (k) as follows:

Equation (10) $\quad \dot{K} = sY\text{-}dK$

Investment changes in the above relationship can be positive or negative; that is, if the rate of depreciation of a country's infrastructure (which itself depends on the depreciation rate) is greater than the rate of

investment (this also depends on the investment rate and the level of production), capital changes are negative and vice versa (Solow, 1956: 66); Neely (2019: 243-248) In this section, in addition to the concept of capital consumption proposed by Solow, it is necessary to address the concept of "flow-storage".

In economics, one of the ways to examine the level of investment is to pay attention to the level of demand in different areas; in other words, the level of demand guides capital to the path of production that can satisfy demand. Demand itself also has The change in the level of production and national income also changes (Tafzali (2001:238). In the flow-stock model, we consider the flow as the inflow of capital into infrastructure and introduce the stock as the amount of investment that has reached its peak. Flow-stock modeling is based on an important law in macroeconomics; that is, the flows and stocks must balance the constraints of individuals and the economy as a whole in order to The available possibilities are compatible.

These limitations are overcome by the operation of certain relationships between the flows and the warehouse. The interaction between the flows and the warehouse is very important; because these two things affect the future of the economy of any country. Godin, 2014: 1-2; Solow, 1957: 314 (& Caverzasi; For example, the road infrastructure of a country can be explained using this model as the warehouse is the same amount Roads have been built (investment has been made) and given that this road infrastructure will depreciate over the years or there is a need to develop new infrastructure (constraints), policymakers manage the flow of capital (facilities) to the needs and demands of that area.

It is clear that there is a time lag between the time of investment and the results in the infrastructure sector. In this The conditions of this gap cannot be filled immediately and must be adjusted gradually. The larger the capital gap, the more investment it requires, and the greater the level of investment power of a player, the faster the said capital gap is filled (Tafzali, 2002, p. 251-252).

5. APPLICATION OF THE SOLOW MODEL IN THE INTERNATIONAL POLITICAL ECONOMY

Here, an attempt is made to explain the economic model that is used in The previous section briefly introduced the concept of change used in the field of international political economy to explain quantitatively. This claim is in addition to the fact that in Solow's production function, he has dealt with the variables of technology and investment.

These two variables are also very important to Gilpin; because Gilpin considers the difference in the distribution of power between countries to be the two main factors of the technological gap and the economic power of the players to invest. It follows in international political economy. (Spiezio, 1990: 173)

Since in the last few decades the international economy has been under the hegemonic control of the United States and with regard to the hegemonic assumptions in international relations (rule through international institutions and prestige, punishment of wrongdoers, creation of the necessary basis for the formation of relations between players based on the hegemonic order).

On the one hand, the role of the state in the macroeconomy On the other hand, the international economic environment can be considered similar to the environment of the macroeconomy; of course, with a certain amount of difference that will be explained further in the continuation of this difference.

Of course, all this is while Gilpin also makes such a similarity and suggests similarities between the state in the macroeconomy and the hegemon in international political economy. He argues, referring to the American and British systems, that Britain and the United States created and implemented the rules of a liberal international economic order.

British and American policies promoted free trade and the free movement of capital. These great powers provided the international money supply and managed the international monetary system. (Gilpin, 1981: 145)

With these explanations, the explanation continues. The application of the Solow model to international political economy will be discussed, given that this theory was designed in the field of macroeconomics.

5.1. The Labor Force Variable (L) in International Political Economy

Here, attention is drawn to an important point, which is the reduction of the role of the labor force variable (L) at the level of the international economy.

This is not to ignore the effect of international labor force. In other words, in the model explained by Solow in macroeconomics, he considered labor force under the control of the economic policies of the state. In these conditions the government can influence the unemployment rate or the labor force by implementing policies such as inflation targeting (Sandlin et al., 1400:164). The economic explanation of this claim in macroeconomics is that during periods of economic prosperity when the volume of aggregate demand increases, the price level increases in line with demand, and vice versa; that is, during periods of recession and decline in the level of Prices fall and inflationary pressures also decrease (Tafzali, 2002:593). Also, the diagram known as the Phillips curve uses statistical data to show the inverse relationship between inflation and unemployment.

However, it can be argued that such conditions do not exist at the level of the international economy, even in the presence of an economic hegemon. At first glance, this criticism can be justified by the last line in the above paragraph. It was argued that an economic hegemon with the global currency it possesses can implement its economic policies at the level of the international system; in other words, a country with global currency (at least in theory, although there is historical evidence for this) can, by creating money without any practical support, transfer some of the financial and inflationary burden of its economy to countries that use its currency.

On the other hand, after the 1870s, with the internationalization of production, the international division of labor, and the emergence of multinational corporations, labor power is no longer limited to workers within the borders of a country; the economic hegemon can now implement economic policies on other countries with the inflationary tools it has at its disposal through its globalism.

In response, it can be said that although there is a The value of the world currency set by the hegemonic player will affect the production and economy of other countries, but this does not mean that the hands of other players are tied. Such an argument is only valid for countries that have pegged their currency (so to speak) to the world currency or that use the world currency directly. It is obvious that countries will try to maintain the policy lever as much as possible. They are self-governing economies, that is, they regulate monetary policies and do not easily provide this opportunity for others to intervene in their economies. In other words, by floating the prices of countries in the international system, economic policymakers can control the effects of world exchange rate changes to some extent by manipulating their domestic exchange rate, and this tool is like a buffer against international financial and economic fluctuations. Use. In other words, the globalization of a currency does not provide sufficient tools and space for a full impact on the national economies of other countries.

This answer is not about denying the impact of changes in the world value of the economic hegemon on the equations of production and the international economy; rather, it is about denying the self-dependence and the essence of the direct relationship between changes in the world value of the currency and the equations of production within other countries.

In response to the second part of the critique based on the internationalization of production, it can also be said that international production and the global division of labor mean the use of the cheap labor capacity and the comparative and competitive advantages of other economies, not the control of the workers and resources of other countries.

As a result, from the general form of this critique, it cannot be concluded that an economic hegemon can control the domestic economy of countries by virtue of having a global price. controlled, arrived; therefore, a country can remove itself from the international production cycle whenever it wants, which of course is far from expected, assuming that the players are rational; except for political and security reasons that do not currently apply in this field.

Also, as mentioned above, in his model, Solow is concerned with the discussion of per capita production, by dividing the production function by the labor force variable in percent, so that the effect Consider only the capital variable.

Although this has been examined in the capital section, the purpose of referring to the per capita production function here was to reach the conclusion that, in addition to the arguments presented above, through the mathematics used in this economic model, the effect of labor can be ignored under certain conditions.

5.2. Technological Variable (A) in International Political Economy

Solow defines technology as a way of doing a job; in a way that leads to any leap in the rate of production compared to previous methods; therefore, the increase in speed, quality and efficiency in production can be classified as a technical leap. (Solow, 1957: 312)

However, here, an attempt is made to establish a conceptual connection between technology in economics and politics. The discussion of technology is of great importance in international relations and the international economy. The importance of this component in military affairs is not hidden from anyone.

Throughout history, any country that has acquired a superior military technology has subordinated other players to a certain extent until it has the upper hand in this technology; a clear example of this claim was the United States' acquisition of the nuclear bomb. This country, due to its nuclear capabilities, has Forced to evacuate Iran's borders after World War II.

However, what has received more attention is the role of technology in international political economy. The British Empire was the first to experience the Industrial Revolution, expanding its fleet across the world's oceans and providing the conditions for the sun to never set on its borders. The United States was the second to experience the Industrial Revolution, becoming a financial and commercial center. It moved the world from London to New York and, through the information technology revolution, managed to maintain and continue its hegemony over the international economy.

In macroeconomics, Solow placed the technological component alongside the labor force variable in the production function equations; but in international political economy, technology can be considered an independent variable.

Although in the previous sections of Control and We have shown the obvious effect of hegemony on labor force in international political economy, the hegemony's control and domination over technology is undeniable. History bears witness to the claim that whenever a country has achieved economic and military hegemony, it has been at the forefront of other countries in a particular technology at that time. And if a country has fallen from the position of hegemonic power, it has been due to the emergence of a technological pole or the loss of advantages. It has been scientific and scientific.

For example, Britain, which for several centuries had been the technological leader among countries, ensured its dominance over international trade by changing its ships first from sailing to steam and then to ships with diesel engines. Thus, a hegemon seeks to maintain its economic, security, and military superiority and advantages by uniting the possible Protect its technological achievements.

This is important for a hegemon against its competitors in two ways: First, if a hegemon's competitors acquire a technology that has created superiority for a country, it will practically neutralize the advantage of the said country and create the basis for creating a threat through the same technology to the dominant power in the economic and security spheres (such as the Soviet Union, which acquired the nuclear bomb). The United States faced many security threats, other than military and security issues (or, with the spread of the Industrial Revolution to Germany, Britain felt a serious threat in overseas markets); second, disgruntled players, in addition to gaining access to a superior technology that was exclusively available to the dominant player, could also neutralize the hegemonic advantage and upgrade it in a way that the dominant player could not. It does not have the conditions for competition in that area for any reason. This situation could pose a greater threat to the hegemon in various fields than the previous one.

It would not be unkind to mention this example here that the executive order should be based on the prohibition of investment by American companies in the semiconductor, microelectronics and quantum industries of China (B iden Orders Ban on Certain US Tech) (Investments in China, Reuters, 2023 is more likely due to the latter. Because China currently has significant capabilities in the aforementioned industries that are undeniable, although it may not yet be as capable as the United States.

China has also made great progress in other technologies that rely on the aforementioned industries, such as artificial intelligence and quantum computers, and may overtake the United States in the near future. Let's say; the government should now try to slow down the pace and speed of China's progress in these areas in order to prevent such a disaster.

In summarizing this discussion so far, it can be said that using the Solow model to explain hegemony issues in international political economy seems to require some changes. The first change is to ignore the labor force variable (L) in this equation due to the inability The effective impact of the economic hegemony on labor force at the level of the international system is unique. The second parameter is the level of technology (A), which is considered as the labor force coefficient in the Solow model; however, in this study, due to the undeniable role of hegemony's dominance over sensitive and strategic technologies, it will be considered as an independent variable. It should be noted that the capital variable is also important due to the effective control of the hegemony. The economy at the level of the international system will be preserved in this equation.

In general, it can be said that although we have ignored the effect of the labor force variable in the production function equation, through the hegemonic control over technology, this component will replace the labor force variable in equation (3). Now, the equation considered for this study will be rewritten as follows: Equation (11) $Y = F (K, A)$

Also, considering that in equation (11) production depends on the technological variable, it is possible to increase productivity with advances in technology, overcome challenges such as depreciation and increasing costs, and even define new areas for development.

It is worth mentioning that here, the importance of the homogeneity of this function (equation 11), which was mentioned in the introduction of the Solow model, becomes more clear. When a leap in technological and capital variables occurs, according to this model, it can be claimed that a hegemon can increase or decrease its output several times.

5.3 Capital Variable (K) in International Political Economy

Solow introduces the production institutions (including land, mineral reserves, etc.) as capital in his model. (Solow, 1957: 314) Compared to the labor force variable, the conditions of the capital variable are very different; in other words, unlike the labor force variable, the economic hegemon did not have the ability to exert a high influence on other economies in this way, in this section Hegemony can have tangible effects on other players. Economic hegemony can influence international capital flows by imposing financial and investment restrictions. The most important tool for this influence is financial and investment "embargoes". Although the application of trade and diplomatic restrictions has a long history in the history of international relations, it can be safely said that Today's financial sanctions are a new generation of sanctions that are much more effective than other sanctions.

These sanctions are aimed at contracting the economic, monetary, financial, industrial, and service infrastructure of the target countries by the economic hegemon, thereby creating serious disruptions in the economies of the target countries. The complementary role of the boycotting and boycotted players is played by other economic players, for whom the logic of the boycott is also a cost-benefit logic.

Thus, third countries must either abandon the economy of the boycotted country for the long-term benefits of economic cooperation with the hegemon or accept the risk of being boycotted for the short-term benefits of playing the banned game. It is clear that players under normal circumstances will choose the first option; unless political and security considerations influence the players' calculations.

By generalizing the model described above to the level of the international economy, what is of great interest in the first part of the Solow model is the variable role of capital. In other words, the more capital a country invests in international political economy, the more it will benefit. In order to maintain and sustain its hegemony over the structure of the international system, an economic hegemon must be able to invest heavily in international affairs.

The second axis of Solow's growth model is devoted to examining the temporal changes in capital. The term capital changes refers to the accumulation of capital resulting from an increase in investment or a decrease in capital due to depreciation.

The increase in investment in the international system can be interpreted as depending on the economic power of the hegemon in strengthening the infrastructure it has created to establish order and maintain the status quo, and depreciation can also be understood as the wear and tear resulting from the use and utilization of security, political, and institutional infrastructure. To keep its players satisfied and maintain the legitimacy of its system, a hegemon must provide free rides in some areas, especially in the area of public goods at the level of the international system, such as security. This requires increased investment by the hegemon to maintain the efficiency of the existing international structure and order in the face of the new needs of the international system and players. It is clear that the hegemon needs large investments to meet the needs and demands, some of which were mentioned above, and also to overcome the challenge of depreciation.

The figure below shows the effect of the depreciation rate on the Solow model. In this diagram, where the depreciation rate is shown as a line, it can be seen that from a point onwards, production costs increase to a point where the depreciation rate makes it uneconomic for the economic actor to increase production, and the rational behavior for the actor would be to maintain the production level before the point so as not to suffer losses (although in the long run, this would also be due to increased depreciation of the infrastructure). will be forced to reduce its production again). This logic well explains the behavior of great powers and hegemons during the period of expansionism and the acceptance of great roles at the level of the international system.

A great power or hegemon must stop expansionism before reaching the point of loss and its own interests and institutions in the international system become exhausted; Of course, this argument has two exceptions: advances in technology (which were discussed in previous sections) and increased investment, which will be discussed further.
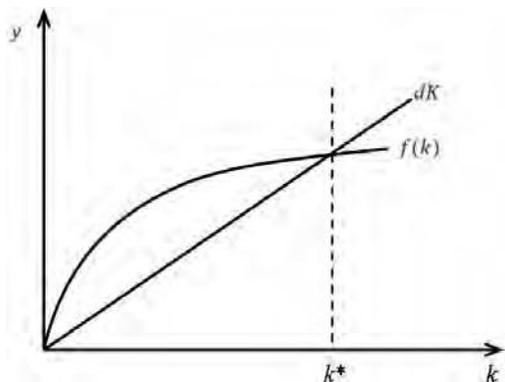

Figure 2. Production function in the Solow model along with the consumption function (Solow, 1956: 70)

One of the conditions that helps the hegemon to continue its voluntary development is the increase in investment. The effect of capital changes can also be seen well in Figures 2 and 3. In function (0), investment has been made with the amount of capital, it can be seen that the depreciation function cuts off this function (0) faster than the function with the amount of capital (0). This figure means that with more investment, the time when consumption and production reach equilibrium can be delayed. In the international relations dimension, it can also be argued that the more a hegemon invests compared to its competitors and the more it depreciates its international infrastructure, the longer it can impose its will on others than if it invested less.
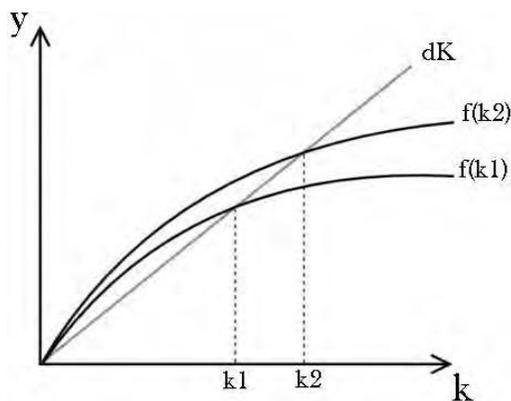
Figure 3. Changes in capital volume in the Solow model (Neely, 2019:245)

So far, the depreciation of hegemon's infrastructure has been examined without the presence of a rival or competitors who try to challenge the hegemon's legitimacy. In the presence of a rival, the use of the flow-storage model seems desirable. In these circumstances, two situations can be considered.

1: The existence of tension between the hegemon and a disgruntled player.

2: War between the hegemon and a disgruntled player.

In the first case, the two sides face disruptions in each other's investment flows in a tense space; as a result, investments are not spent in the right places. The best example of this situation is the arms race. The Cold War arms race between the United States and the Soviet Union distracted the developing superpower from investing in its own domestic affairs and focused its attention on posing a threat to Western interests and economic aid to its allies.

Or, institutionally, the Soviet Union pitted the Warsaw Pact against the NATO alliance with its allies in order to challenge this institutional capacity of the United States-led West. In such a situation, where the legitimacy of the existing order is challenged, the hegemon must defend its infrastructure against disgruntled players at greater cost.

The more serious the challenge from disgruntled players, the more serious the process of disrupting the hegemon's infrastructure investments at the level of the international system will be.

In the second case, when war breaks out, not only is the flow of investment disrupted (because the parties spend their capital on defeating the opponent), but the depreciation of infrastructure also increases exponentially; in other words, in addition to normal depreciation and disruptions in the flow of capital, the infrastructure itself (the investment that has been put into operation) is directly damaged.

Whichever side emerges victorious from this hegemonic battle, in addition to gaining prestige, eliminates the threat from the other side, either for a very long or a short period of time; as an example, the threat from Germany was eliminated after World War I until the rise of Hitler, and has been eliminated for the Anglo-Saxon order since World War II. What is important here, as a summary, is the decline of the hegemon or the hegemon's rival in one of the three capital depreciation conditions that have been introduced:

1. The high rate of depreciation of the hegemon's infrastructure and the inability to manage this depreciation.

2. In addition to the depreciation of infrastructure, the investment process and capital flows are disrupted;

3. War is also added to the two factors above, which ultimately determines the fate of the post-war hegemonic order and international system.

6. CONCLUSION

What has been examined so far has been an examination of two readings of realism based on the views of Kenneth Waltz and Robert Gilpin. Waltz's reading seems too abstract due to its excessive focus on contemporary military and security issues.

Today's world is moving towards more complex economic equations, and in many cases, military issues are also intertwined with economic transactions. For example, how can Waltz's logic explain the competition between China and the United States, while these two powers are each other's largest trading partners, or the economic transition conditions that, given the evidence of China's economic behavior, could lead to changes in the international political economy system? It is clear that Waltz's logic is very ineffective in explaining such conditions. In contrast, Gilpin's reading, by providing a broad framework and the possibility of using both international economics and international politics, has the potential to respond to the needs of the current situation.

In international political economy, Gilpin discusses hegemonic stability, and in international politics, he examines the types of change within the framework of the hegemonic cycle. In this study, using these two discussions alongside Robert Solow's economic model, a framework was provided to explain the change in international political economy, which focused on variables such as technology, capital, and international

economics, which seemed desirable to explain the transitional conditions in the field of international political economy.

The choice of the aforementioned variables is important because the level of benefits that an economic hegemon achieves at the level of the international system depends on two factors: the level of investment in the international system and the level of technology. As long as the hegemon has the ability to invest heavily in the international economy and politics and is a pioneer in the field of technology and innovation, its power will continue; But if the player or players are dissatisfied with their ability to outpace the hegemon in the areas of capital and technology, the ruling hegemon will undoubtedly feel clear limitations on its will. In general, what was examined in this study was the use of Robert Gilpin's theories in the fields of international politics and international political economy, which was strengthened and enriched by Robert Solow's economic model to better explain the cycles and changes in the international political economy system.

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Human Capital and Digital Skills as Drivers of Firm-Level Competitiveness in Azerbaijan's Transition Economy

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Abstract; As Azerbaijan continues its economic transition, the development of human capital and acquisition of digital skills have emerged as vital factors shaping firm-level competitiveness. This article examines the ways investments in education and digital competencies enhance productivity, foster innovation, and improve market positioning among Azerbaijani firms. Drawing from national statistics, international case studies, and relevant theoretical frameworks, this study highlights the evolving role of digital transformation within the country's post-Soviet economy. It also offers strategic recommendations and policy implications aimed at cultivating sustainable competitive advantages through human capital and digitalization.

Keywords: Human capital, digital skills, firm competitiveness, Azerbaijan, transition economy, digitalization, labor market

1. INTRODUCTION

Azerbaijan, a resource-rich country located in the South Caucasus, has been navigating a complex economic transition from a Soviet-command system toward a market-oriented economy since gaining independence in 1991. Traditionally reliant on the hydrocarbon sector, the nation now prioritizes economic diversification and sustainable growth (World Bank, 2022). In this changing economic landscape, firm-level competitiveness increasingly depends on intangible assets like human capital and digital skills.

This article aims to explore how investments in human capital—particularly digital skills—serve as key drivers of competitiveness for firms operating within Azerbaijan's evolving economy. By integrating theoretical insights with empirical data and international comparisons, this study contributes to understanding how productivity and innovation can be enhanced in transition economies (Рустамов & Алекперов, 2012). This focus is especially relevant as digital transformation accelerates globally, prompting emerging economies to harness these developments for modernization and growth.

2. THEORETICAL FRAMEWORK

2.1 Human Capital Theory and Competitiveness

Human capital theory, developed by Becker (1964) and Schultz (1961), posits that investments in education and training improve worker productivity, which in turn positively impacts firm performance and economic growth. In transition economies, where labor markets undergo structural reforms, developing human capital is critical for overcoming inefficiencies inherited from the past and for adapting to competitive pressures (Barro & Lee, 2013). Education, therefore, should not be viewed solely as a social benefit but as a strategic economic input that equips firms to innovate and compete effectively (Гасымов & Алекперов, 2013).

Human capital extends beyond formal education to include tacit knowledge acquired through experience and continuous learning. This broader perspective is essential for assessing firm-level competitiveness, as it reflects a firm's dynamic capability to adapt to technological and market changes (Teece, Pisano, & Shuen, 1997).

2.2 Digital Skills and the Knowledge Economy

The digital revolution has fundamentally reshaped the competencies required for firms to survive and thrive. Digital skills—which range from basic information and communication technology (ICT) literacy to advanced capabilities in data analytics and cybersecurity—enhance operational efficiency, innovation potential, and market reach (OECD, 2019). Firms with digitally skilled employees tend to outperform their competitors by leveraging emerging technologies for product development and process improvement (Brynjolfsson & McAfee, 2014).

In transition economies like Azerbaijan, digital skills also facilitate integration into global value chains (GVCs) by enabling firms to meet international standards and adopt advanced production methods. The knowledge economy framework emphasizes that competitiveness increasingly hinges on intangible assets such as knowledge, skills, and digital capabilities, which complement traditional factors of production (Powell & Snellman, 2004).

2.3 Firm-Level Competitiveness in Transition Economies

Firm competitiveness can be broadly understood to include productivity, innovation, market share, and adaptability (Porter, 1990). Firms in transition economies face unique challenges including institutional instability, outdated organizational structures, and skill mismatches that constrain competitiveness (Estrin & Wright, 1999; Meyer & Peng, 2016). In this context, human capital and digital competencies serve as crucial enablers, providing firms with opportunities to leapfrog development stages through the adoption of modern technologies and management practices.

Moreover, the competitive environment is dynamic and requires firms not only to acquire new skills initially but to cultivate a culture of lifelong learning and digital literacy to remain competitive amid global market fluctuations.

3. AZERBAIJAN'S ECONOMIC TRANSITION AND LABOR MARKET OVERVIEW

3.1 Macroeconomic Background

Since independence, Azerbaijan has seen substantial economic transformation as it moves from a centralized to a market-based economy. According to the World Bank (2023), Azerbaijan's GDP has grown at an average annual rate of approximately 2.5% over the last decade, although this growth has been volatile due to fluctuations in oil prices. The hydrocarbon sector remains dominant, contributing nearly 40% to GDP and accounting for 90% of exports, which exposes the economy to external market shocks.

Acknowledging this vulnerability, the Azerbaijani government has committed to diversifying the economy by developing non-oil sectors such as agriculture, manufacturing, information technology, and tourism (Ministry of Economy, 2022). These emerging sectors demand new skill sets and digital competencies distinct from those traditionally required, thereby emphasizing the critical role of human capital development.

3.2 Labor Market Characteristics

Azerbaijan's labor market reflects ongoing structural shifts with a growing service sector and increased demand for skilled workers. The State Statistical Committee (2023) reports that the employed workforce has reached approximately 4.4 million individuals, yet youth unemployment remains high at 16.3%, signaling underutilized human capital potential. Additionally, women's labor force participation stands at 52%, indicating persistent gender disparities in workforce engagement.

A key challenge is the mismatch between labor market demands and workforce skills. Many employers express difficulty recruiting candidates with sufficient technical and digital skills, which ultimately hinders firm productivity and innovation (World Economic Forum, 2021). This skills gap is often attributed to outdated educational curricula and limited vocational training infrastructure.

3.3 Digital Infrastructure and Skills Gap

Azerbaijan has made strides in improving digital infrastructure, with internet penetration reaching 82% by 2023 (ITU, 2023). Mobile broadband subscriptions have also grown, providing greater access to digital services in both urban and rural areas. Nevertheless, digital skills remain unevenly distributed, with urban centers exhibiting higher competency levels than rural regions.

A survey conducted by the Ministry of Digital Development and Transport (2022) reveals that only 37% of firms report having sufficient digital skills among their employees, underscoring the urgent need for targeted skill development initiatives. The government's "Digital Azerbaijan 2025" strategy aims to double digital skills proficiency by 2025 through educational reforms and expanded vocational training, though implementation challenges persist.

4. THE ROLE OF HUMAN CAPITAL IN FIRM-LEVEL COMPETITIVENESS

4.1 Education and Training as Productivity Enhancers

Empirical evidence from Azerbaijan indicates a clear positive correlation between higher education levels and firm productivity. For example, a study by Aliyev and Mammadov (2021) focusing on manufacturing firms found that enterprises employing workers with tertiary education experienced 15% higher labor productivity compared to those without such qualifications. This finding is consistent with global research showing that skilled labor reduces operational inefficiencies and enhances product quality (Hanushek & Woessmann, 2020).

Beyond formal education, firms that invest in on-the-job training and professional development programs report improved adaptability and greater capacity for innovation. Firms participating in USAID-supported training initiatives experienced a 10-12% increase in output per worker over a two-year period (USAID, 2021).

4.2 Continuous Learning and Workforce Adaptability

Given the rapid pace of technological change and evolving market conditions, continuous professional development is essential (Ibrahimov et al, 2024). Azerbaijani firms engaged in international markets have increasingly adopted training programs focusing on digital literacy, project management, and leadership skills (USAID, 2021). These investments in human capital enable firms to respond swiftly to market disruptions and technological advancements.

Moreover, fostering a culture of lifelong learning is critical for sustaining competitiveness. Firms that encourage employees to participate in upskilling initiatives tend to experience lower staff turnover and higher innovation outputs (OECD, 2019).

4.3 Human Capital and Innovation Capacity

Human capital is a key driver of innovation, which itself is crucial for competitive advantage. Research by the Azerbaijan Innovation Agency (2023) indicates that firms with R&D teams educated in STEM fields are twice as likely to introduce new products or processes. This aligns with global patterns where skilled human capital supports knowledge creation and technology adoption (OECD, 2022).

Additionally, innovation ecosystems that connect universities, research institutions, and firms strengthen the translation of human capital into competitive advantage. However, Azerbaijan's innovation ecosystem remains in its early stages, with limited collaboration between academia and industry (World Bank, 2022).

5. DIGITAL SKILLS AS CATALYSTS FOR COMPETITIVENESS

5.1 Impact of Digitalization on Firm Performance

Digital transformation equips firms to optimize operations, reduce costs, and access new markets. According to data from the Azerbaijan Export and Investment Promotion Foundation (AZPROMO, 2022), digitally advanced firms exhibited an average revenue growth rate 1.7 times higher than their less digitalized counterparts. This underscores the importance of digital skills as a critical competitive differentiator.

Employees with strong digital competencies enable firms to implement automation, e-commerce platforms, cloud computing, and data analytics. These technologies improve decision-making and enhance customer engagement. For example, Azerbaijani firms using enterprise resource planning (ERP) systems have achieved significant inventory cost reductions and shorter lead times (AZPROMO, 2022).

5.2 Case Study: Successful Digitalization in Azerbaijan's SMEs

The fintech sector offers a clear example of how digital skills drive firm competitiveness. Companies like Kapital Bank have successfully leveraged digital platforms to expand their customer base and improve service delivery, resulting in notable market share gains (Kapital Bank Annual Report, 2022). The bank's mobile application, which incorporates AI-driven customer support and personalized financial products, has been recognized as a regional model of digital innovation.

Similarly, small and medium-sized enterprises (SMEs) based in Ganja have expanded export opportunities by utilizing digital marketing and online sales platforms, overcoming traditional barriers to internationalization (USAID, 2021).

These examples illustrate how digital competencies translate into tangible business success even within a transition economy context (Farzaliyeva & Abdullayev, 2025).

5.3 Challenges in Digital Skills Acquisition

Despite progress, many Azerbaijani firms face significant obstacles in acquiring digital skills due to limited training resources, outdated curricula, and low awareness about the benefits of digitalization (World Economic Forum, 2021). SMEs, which make up over 90% of Azerbaijani enterprises, often lack the capacity to invest in digital upskilling, which hampers their competitiveness.

Moreover, gender disparities persist in digital professions, with women underrepresented in ICT fields, thereby limiting the country's overall talent pool (International Telecommunication Union, 2022). Addressing these challenges requires coordinated efforts involving government, private sector, and educational institutions.

6. COMPARATIVE INSIGHTS FROM GLOBAL EXPERIENCES

6.1 Estonia: A Digital Transition Success Story

Estonia's rapid digital transformation offers valuable lessons. The country has invested heavily in e-governance, digital literacy, and startup incubation, resulting in a vibrant innovation ecosystem and globally competitive ICT firms (World Bank, 2019). Estonia's e-Residency program allows entrepreneurs worldwide to establish firms digitally, enhancing its business climate.

The Estonian experience underscores the importance of coherent national strategies that link human capital development with digital infrastructure. Its education system emphasizes coding and digital skills from early schooling, ensuring a steady pipeline of digitally competent workers.

6.2 South Korea: Human Capital and Technological Advancement

South Korea's remarkable shift from an agrarian economy to a high-tech industrial powerhouse was fueled by sustained investments in education and digital skills (OECD, 2020). South Korean firms benefited from a highly skilled workforce capable of adopting and innovating new technologies, boosting their global competitiveness in sectors such as semiconductors, automobiles, and electronics.

Government-industry-university collaborations played a critical role in aligning skills development with technological needs, highlighting the importance of institutional frameworks in fostering firm competitiveness.

6.3 Lessons for Azerbaijan

Azerbaijan can learn from these examples by encouraging public-private partnerships for digital skills training, reforming educational systems to prioritize ICT competencies, and incentivizing firms to invest in employee development. Institutional reforms that promote innovation-friendly policies and reduce bureaucratic hurdles will further enhance firm-level competitiveness.

It is vital that Azerbaijan tailor these lessons to its unique context, balancing the legacy of its transition economy with ambitions for digital modernization.

7. POLICY RECOMMENDATIONS FOR AZERBAIJAN

7.1 Enhancing Education and Training Systems

Curriculum Modernization: Integrate digital competencies, coding, critical thinking, and entrepreneurial skills into formal education at all levels, with particular emphasis on STEM disciplines.

Lifelong Learning: Encourage continuous professional development through subsidies, tax incentives, and accessible digital learning platforms (Babayev, 2022).

Public-Private Partnerships: Collaborate with industry stakeholders to design curricula and training programs aligned with current and future labor market demands.

Gender Inclusion: Implement initiatives to increase female participation in ICT education and professions to expand the talent pool.

7.2 Strengthening Digital Infrastructure and Access

Broadband Expansion: Prioritize internet access in rural and underserved regions to foster inclusive digital participation.

Digital Literacy Campaigns: Raise awareness among SMEs and the broader population about the benefits of digitalization via workshops, media campaigns, and government initiatives.

Support for Innovation and Technology Adoption: Provide startups and SMEs with access to financing, mentorship, and technology through innovation hubs and accelerators.

7.3 Institutional Reforms and Incentives

Regulatory Frameworks: Simplify administrative procedures for digital business models, including e-commerce and fintech, while ensuring data privacy and cybersecurity.

Incentives for Skill Development: Offer grants, tax breaks, or co-financing schemes to firms investing in employee digital training and innovation activities.

Monitoring and Evaluation: Develop metrics and conduct regular assessments to evaluate the effectiveness of human capital and digital skills programs, guiding future policy adjustments.

Encouraging Collaboration: Promote stronger linkages among universities, research institutions, and firms to enhance innovation ecosystems.

8. CONCLUSION

Human capital and digital skills are central to driving firm-level competitiveness in Azerbaijan's transition economy. As the country pursues diversification and modernization, prioritized investments in education, training, and digital competencies are essential. Drawing on global experiences, Azerbaijan can craft strategic interventions to close skills gaps, boost innovation, and foster a competitive business environment (Mammadova & Abdullayev, 2025).

The interplay between human capital development and digitalization will ultimately determine the sustainability of firm competitiveness amid evolving market conditions. Firms with skilled, digitally literate workforces will be better positioned to face global challenges, integrate into international value chains, and contribute to national economic resilience.

Focused policy action on education reform, digital infrastructure expansion, and skill acquisition incentives is crucial to unlocking this potential (Abdullayev et al, 2024). Ultimately, the transformation of Azerbaijani firms through human capital and digital skills development will underpin the broader economic transition and long-term prosperity of the nation.

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An Overview of the Challenging Paths Ahead for the Future of Artificial Intelligence Law

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Abstract; Today, artificial intelligence, using its capabilities such as text and image processing, has many applications in education, health and wellness, career development, personal affairs, and even law. Among its applications are the analysis of raw data for research, content production, disease detection and identification, and marketing.

Therefore, artificial intelligence is progressing at a rapid pace, and its monitoring is visible in our lives and work and in the not-so-distant future, it will cover an important part of our lives. Therefore, it is important to understand the paths and challenges facing the future of artificial intelligence law.

In this regard, this research discusses the relevant field of artificial intelligence law, and also considers what kind of regulatory issues artificial intelligence projects at the national and international levels can add to the current digital law discourse.

Relying on the literature on artificial intelligence law, this research points out other problems related to the subjectivity of artificial intelligence law and the real personality of artificial intelligence that have not yet been recognized in digital law.

Keywords: Digital Rights, Artificial Intelligence Rights, International, Privacy, Intellectual Property

1. INTRODUCTION

It is no coincidence that artificial intelligence is one of the most widely used terms in all branches of the transhuman sciences. The idea that machines can become equal in intelligence and perception to humans has occupied many writers and scientists for decades.

From the computer system in the film A Space Odyssey to the superhuman androids in the Western world, all prove that artificial intelligence has encompassed a wide range of human imaginations. On the other hand, the study of law and information technology is accompanied by an inherent contradiction, because while technology encompasses concepts such as internationalization and globalization, law, in most cases, is still limited to a certain extent by national borders.

Partly overcoming this contradiction is the concept of the rule of law, which contains within itself the idea that "the rule of law is good for everyone," a view that apparently enjoys international support.

It is acknowledged that this strong support for the rule of law is based on different interpretations of what the rule of law is and in some cases may even be hijacked by those who wish to use it as a cover to hide actions that contradict its ideals. However, in most cases, the rule of law remains an ideal, similar to the concept of "good," in the sense that everyone supports it but has conflicting beliefs about what it is.

However, as society becomes increasingly digital, a second, more subtle threat is on the rise. This threat comes from technology, particularly technology that includes elements of artificial intelligence. As great

strides are being made in the academic field of artificial intelligence, this technology is making its way into digital decision-making systems, which in turn are replacing human decision-makers, institutions, both public and private, that are seeking to increase their effectiveness.

Human decision-making is currently assisted by digital decision-making systems and this function is increasingly given to machines, the field of governance is no exception. The threat to the rule of law lies in the fact that most of these decision-making systems are "black boxes", because they use very complex technology that is fundamentally beyond human cognitive capacities, and the law also prevents transparency to some extent.

It is here that the fulfillment of the demands of the rule of law, such as insight, transparency, fairness and explainability, is almost impossible, which in turn raises questions about the extent to which the rule of law is a viable concept in a technocratic society.

Therefore, given that in recent years, especially the past year, the growth of artificial intelligence has shaped human social life, the main question and issue is what is the legal path and legislative challenges in the future of artificial intelligence? Will regulating this technology remain an opportunity for the future and human life? The present research method is library and documentary.

The data is from the most authoritative and latest domestic and foreign scientific studies focusing on intellectual property rights. The data analysis method is also descriptive-analytical.

2. RESEARCH BACKGROUND

Hanieh Zakirinia, (2023), The Nature and Basis of Civil Liability Arising from Artificial Intelligence in the Laws of Iran and the European Union. Today, it is essential to adapt regulations to new technological challenges. Therefore, choosing a clear and coherent civil liability regime for artificial intelligence will be crucial.

National laws differ and offer varying degrees of flexibility to adapt to the challenges of artificial intelligence. Fault-based liability is a general assumption in most European legal systems. In the laws of some countries, the liability of artificial intelligence can be explained as liability for the acts of others based on customary invocation. When there are multiple responsible parties, joint liability can be justified.

Mohammad Mehdi Davar, (2023), Authorizing the Ethical Use of Artificial Intelligence Using Farabi's Theory of Natural Rights and Happiness. The discussion of artificial intelligence as an emerging phenomenon in the present era has always faced numerous ethical challenges. The spread of artificial intelligence is inevitable, and since this phenomenon is related to the human and social world, and everything related to humans and society falls within the realm of ethics and law, it is necessary to know whether the use of artificial intelligence is ethical or not? And also, do humans have the right to use it or not? It seems that Farabi's thought in the field of practical wisdom can answer this issue.

By reflecting on the theories of this prominent philosopher in civic wisdom, the theory of natural rights is received, and on the other hand, Farabi's ethical views are also in harmony with the theory of natural rights and with Farabi's civic wisdom in general. Therefore, it is possible to consider and explain this issue according to Farabi's ethical and civic school.

Anahita Seifi and Nejm Harzamkhah, (2022), Artificial Intelligence and the Challenges Ahead in the Field of International Human Rights, An Approach to the Right to Work. Despite the various benefits of "artificial

intelligence" in human daily life, the world has witnessed the undesirable effects of its use in various areas, including the job security of the weak and vulnerable segments of society due to the automation of some jobs; an issue that can entail a violation of one of the fundamental human rights, namely the right to work. However, according to the provisions of the International Bill of Human Rights, governments not only have the duty to implement and ensure the right to decent work, but also must refrain from creating any obstacles in the process of enjoying this right. Therefore, the main question is what should be done in the conflict between the benefits of using artificial intelligence and the fundamental right to work and having job security? It is certain that, given the obligations that governments have to ensure and implement the right to work, they must, in addition to providing the necessary conditions to ensure welfare and new employment opportunities for people who have lost their jobs due to the automation of some jobs, provide facilities to provide the necessary training in society to become more familiar with artificial intelligence and its applications with the aim of increasing the productivity of this new technology in society.

Stanley Greenstein, (2022), Maintaining the Rule of Law in the Age of Artificial Intelligence. The study of law and information technology is accompanied by an inherent contradiction, because while technology is developing rapidly and encompasses concepts such as internationalization and globalization, traditional laws can in most cases be slow to respond to technological developments and are also largely limited to the national level.

However, a serious threat to the rule of law is emerging in the form of an attack by technological advances in artificial intelligence. As the academic field of artificial intelligence makes great strides, this technology is making its way into digital decision-making systems, effectively replacing human decision-makers.

A prime example of this development is the use of artificial intelligence to assist judges in judicial decision-making. However, in many situations, this technology is a black box, mainly due to its complexity, but also because it is protected by law.

This lack of transparency and the reduced ability to understand the functioning of these systems, which are increasingly used by governance structures, challenge traditional concepts of the rule of law. This is especially true in relation to concepts that are particularly relevant to the rule of law, such as transparency,fairness and explainability.

Sylvia Wotczak, (2022), Granting Legal Mindfulness to Artificial Intelligence. This article addresses the problem of granting legal mindfulness to artificial intelligence, especially with regard to civil law. The myth that the criteria for legal mindfulness are emotion and reason must be rejected.

The argument that AI may have potential legal subjectivity, based on the analogy with animals or legal persons, suggests the existence of a hierarchy of entities organized according to their degree of similarity to humans. Also, the place of an entity in this hierarchy determines the scope of subjectivity attributed to it.

Rather, participation or presence in social life, whatever its role, is the real criterion of subjectivity. Moreover, it is clear that even if AI does not currently participate significantly in social life, it will in the near future. Despite the potential risks associated with attributing a kind of subjectivity to AI, such periods are inevitable and should be considered sooner rather than later.

3. ARTIFICIAL INTELLIGENCE; DEFINITION AND CONCEPT

The image below provides a better understanding of the definition of artificial intelligence. Machine learning and deep learning have similarities and differences. The similarity between these two areas is that both use algorithms to design machines with special functions that do not require human intervention.

The most important difference between deep learning and machine learning is that in deep learning, the algorithms have more layers and are more complex. Therefore, artificial intelligence is a program that is inspired by human intelligence and is implemented on machines. In this way, the machine can do the same things that a human does in a shorter time and with greater accuracy (Davar, 2023)
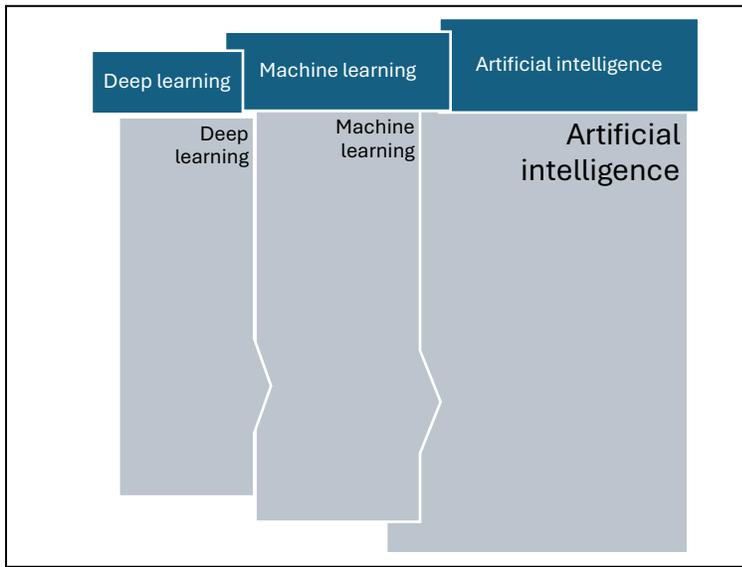

Figure 1. Difference between the three concepts of artificial intelligence, machine learning and deep learning.

Programs are often implemented on computer systems, and through this program, the computer can make decisions, plan or predict the outcome of the problems presented to it.

Components of artificial intelligence applications:

First - Machine vision: It is a technology that attempts to provide a type of vision for machines. Machine vision is used in various industrial processes from face recognition, video analysis and object recognition to pattern recognition.

Second - Speech processing: Speech processing systems enable intelligent machines, such as smartphones, to communicate with users through spoken language. Probably the most famous speech recognition technology you have heard of is Apple's product.

Third - Data mining: As the name suggests, it is related to the field of data analysis, especially big data. In fact, in data mining, the task of extracting patterns from data is attempted to be left to machines. With this brief explanation, it can be understood how important data mining can be, because patterns extracted from business data can provide very useful information for future plans of companies. This branch of artificial intelligence is a combination of statistical tools and artificial intelligence with the management of aggregate data. Data mining usually has wide applications in business (insurance, banking, etc.), scientific research (astronomy and medicine), and security issues (detecting criminals and terrorists).

Fourth- Natural Language Processing:

Natural language processing is the teaching of human language to machines. This part of artificial intelligence is where natural language and artificial languages (such as programming languages) come together. Efforts to process language with the help of computers have a longer life than many branches of artificial intelligence.

Najm- Machine Learning: Machine learning and its related concepts are a subfield of artificial intelligence that is related to the ability of machines to learn; in fact, machines are able to learn and improve automatically without being programmed to learn in advance.

Therefore, machines in different places are able to work with data and can improve their learning with the data received. Machine learning is the automatic learning of computers, and its goal is for computers to reach new patterns and make better decisions as a result of working with data.

Machine learning is now used in every industry and job.

Therefore, there are four main groups of artificial intelligence systems, namely: first - "reactive machines" the most basic type of artificial intelligence, second - "limited memory" with decision-making power, third - "theory of mind" with the ability to think, fourth - "self-aware artificial intelligence" with the ability to intuition and empathy, and the stages of evolution of this technology are parallel and continuous.

Artificial intelligence generally refers to any human-like behavior performed by a machine or system. In the most basic form of artificial intelligence, computers are programmed to "imitate" human behavior using extensive data of similar behavior samples. This behavior can range from distinguishing between a cat and a bird to performing complex activities in a manufacturing center.

With artificial intelligence, machines can work efficiently, analyzing vast amounts of data in the blink of an eye, and solving problems through supervised, unsupervised, or semi-supervised learning.

4. LAWS AND ARTIFICIAL INTELLIGENCE FROM A LEGISLATIVE PERSPECTIVE

One of the challenges posed by the expansion of artificial intelligence is the need for legislation in this emerging field. Every new phenomenon in societies requires laws that determine and guarantee the rights of individuals.

Although at first glance and in some cases, current laws can be applied to new phenomena, the need for new laws is certainly felt in light of the innovations created. For example, identity fraud using artificial intelligence becomes easier and increases, and cybercrimes that occur using artificial intelligence require precise regulations to prevent and control them.

With the expansion of artificial intelligence-based programs and their use in various jobs, issues such as civil liability arising from decisions and the performance of artificial intelligence will also be of great interest and a subject of discussion and research.

If an act performed by artificial intelligence harms someone, who is responsible for it? An issue that has also been the subject of much debate in self-driving car technology is who is responsible if a car has an accident while driving itself? There are also issues raised in the discussion of intellectual property, such as what will be the form of intellectual property rights if artificial intelligence reaches a stage where it can have its own works and inventions? All of these issues and many other topics will be the subject of much

research and discussion in order to find appropriate answers and solutions to the questions and challenges ahead in this field (Saifi and Razmkhah, 2022).

5. PROVISIONS OF THE 2024 CONVENTION ON ARTIFICIAL INTELLIGENCE

The Council of Europe's human rights body announced that the first legally binding international treaty on artificial intelligence was ratified in 2024 by the member states of the European Union, the United States and the United Kingdom.

The Convention on Artificial Intelligence, which has been in the process of being drafted for several years, was adopted in May after discussions and negotiations between fifty-seven countries. The Convention, while promoting responsible innovation, also addresses the potential risks of artificial intelligence. The Convention focuses mainly on protecting the human rights of people affected by artificial intelligence systems and is separate from the EU's AI law.

The EU's AI law includes comprehensive provisions on the development, deployment and use of artificial intelligence systems in the EU's internal market. The UK's Justice Secretary said in a statement: "This convention is a major step towards ensuring that these new technologies can be used without undermining our most ancient values, including human rights and the rule of law, and are, where necessary, restrained."

The Council of Europe, founded in 1949, is an international institution distinct from the European Union that works primarily in the field of human rights protection. This international institution, which was established on the basis of the development of democracy, human rights, the rule of law and the exploitation of cultural cooperation, has forty-seven member states, including twenty-seven EU member states.

A special committee within this institution began the necessary studies in 2019 to develop a convention on artificial intelligence, and this process was followed in 2022 by the formation of other committees to draft the text of the convention and continue negotiations on its contents.

6. FINDINGS

After examining the research topic, important factors related to the "future challenges of AI law" were deduced, which are:

6.1 Possibility of abuse of power

Krieger's argument is that the rule of law is fundamentally about power, where its main purpose is to make the law govern in order to prevent the possibility of abuse of power by those who use this power in an arbitrary manner. He states that there are many ways to exercise power and arbitrary ways should be avoided.

It is in this context that the Venice Commission's criterion for "preventing abuse of power" is relevant. There is a correlation between the definition of the rule of law from the perspective of power on the one hand and the concept of mutual interaction on the other.

For mutual relations to flourish, a certain balance in the power relationship between rulers is necessary. However, it is argued that the transfer of government to technology, as we saw in the Loomis case, entails a monopoly on access to technology.

Essentially, only those who govern have the resources to produce or purchase the technology that is used to make decisions about citizens. This ever-increasing imbalance disempowers the rulers in favor of the ruled.

For example, by consolidating power over technology in the hands of the rulers, the risk of unrestricted executive powers increases, which is contrary to the rule of law as stated by the Venice Commission. Furthermore, an aspect of the abuse of power identified by the Venice Commission is irrational decisions.

However, to what extent can decisions made by AI be challenged as "irrational" when they cannot be understood at first, but also when human rationality is not necessarily a prerequisite for an algorithmic solution? A final complication in the balance of power is the fact that the producers of AI technology are private actors, the balance of power essentially having to be achieved between three entities, namely those who govern, those who are governed and the private companies that develop the technology to mediate.

The Venice Commission also recognises that there may be circumstances in which private actors exercise powers traditionally exercised by states. However, the examples given include the management of prison services and it is argued that situations in which private actors take over the discretion of judges have never been foreseen.

6.2 Challenging traditional legal protections

The increasing use of AI to predict human behavior, especially criminal behavior, also challenges some traditional legal concepts. One of the legal concepts that is being challenged is that the accused is presumed innocent until proven guilty.

For example, the use of algorithmic risk assessment in criminal trials to determine recidivism raises the question of whether the accused is presumed to be guilty of a potential crime, i.e., the propensity to commit a crime before it actually occurs. This is well-recognized in the principles that recognize that there is no crime or punishment without law, which are also included in the Venice Commission.

The presumption of innocence and the right to a fair trial are also included in the Venice Commission's standards on access to justice. Another challenge to the traditional view of the rule of law is the extent to which the judiciary can be considered independent by relying on AI developed by private companies. The Venice Commission calls for legal guarantees to ensure the independence of the judiciary.

According to the Venice Commission, independence means that the judiciary is "free from external pressure". While companies that produce algorithmic risk assessments may not directly pressure judges, the question that needs to be asked is to what extent individuals (judges, juries and probation officers) dare to act against the risk assessment made by technology. This in turn raises issues of a philosophical nature in which technology is endowed with a degree of autonomy.

Elwell argues that technology has acquired an autonomy from its connection to the legitimacy of scientific progress in general. In other words, technology has legitimacy because of its scientific and objective conception.

6.3 The Challenge of the Nature of Legal Personhood

The Claimed Hierarchy of AI? In the literature, two key analogies are used when discussing the possibility of attesting to legal personhood or legal personality for AI systems: one between AI and animals and the other between AI and legal persons or collective entities.

Many scholars agree that legal subjectivity in the form that has been attested to a human is unique to the individual and cannot be attested to AI, especially since, at least for now, AI shows no evidence of being conscious or intelligent.

In contrast, the analogy with animals seems more appropriate, since AI's capabilities are limited in relation to humans. On the other hand, AI can be considered analogous to collective entities, in the sense that it is an artificial being, a non-living creature lacking feelings and consciousness.

Moreover, according to the traditional Western view, animals and legal persons are the only real candidates for a broader or more limited legal subjectivity alongside humans. Many foreign jurists would be surprised to learn that in some countries or cultures, rivers are also recognized as objects of law, such as the Ganges Jamuna in India and the Wanganui in New Zealand. However, using the analogy with animals or legal persons to justify granting potential legal subjectivity to AI requires a certain superficial assumption.

First, the analogy assumes that there is a hierarchy or sequence of entities organized according to their degree of similarity to humans, and second, that a being's place in this hierarchy or sequence (based on the degree of development) determines the extent of the subjectivity attributed to it.

Animals, therefore, occupy the lowest position in the hierarchy, because, despite possessing sentience, they lack the reason traditionally considered to be a fundamental and uniquely human characteristic.

Similarly, contemporary AI, which lacks sentience and whose reason is incomplete, could occupy the next position. The next place in the hierarchy is occupied by collective entities, because they lack feeling, but they have collective reason. Such reason corresponds to human reason and may surpass it because its context is human.

Finally, at the top of the hierarchy are humans. These are intelligent and have reason, which according to traditional views is the best prototype of its kind. Taking this line of thinking into account, it can be predicted that if artificial intelligence develops to the point where it can achieve full reason or a form superior to human reasoning, and if it acquires some feeling, it will rise above collective entities and be ranked.

On a par with humans Advocates of this view believe that artificial intelligence cannot acquire a legal subjectivity different from that enjoyed by animals or collective entities, but must be similar and derivative. Thus, in a given legal system, collective entities may have some rights that are specific to humans but not attributed to animals, which are granted on the basis of similarity. In such a system, AI is superior to animals, which may have rights similar to those of humans. A good example of this type of thinking is illustrated in copyright law:

It has been argued that AI cannot be recognized as an author based on various cases involving animals, most notably the famous monkey selfie case.

6.4 Participation or Presence of Artificial Intelligence in Social Life

Considering the above and considering granting legal subjectivity to AI, two key questions arise:

First, does AI participate in social life?

Second, does AI have or will have intrinsic value or utility for social relations? In answering these questions, it should be remembered that the assumption is that AI will imitate or surpass a man, at least in one

important area, or perhaps all of them. Of course, such an assumption requires imitating or surpassing positive aspects or personalities, and not negative aspects evaluated according to human standards.

With regard to the first question, when observing the commercial market, it is clear that AI will soon participate in social life, even if it does not currently, despite the fact that many people believe the opposite. Even insisting that AI does not have the potential to make decisions, but a human has the power to do so, and that AI only provides a basis for human decisions, namely the result of reasoning, it cannot be denied that AI communicates with it.

A man has the ability, through an understandable language, to influence his decisions and personality. This is a much more advanced function than a simple calculator used to calculate the price when buying a product.

It is more of a "role" than a "function". However, at this point it is important to highlight a different reality from common belief: it is not the autonomy of AI's action that is the most important consideration.

Even the most self-driving car will only be a means of travel, assuming it is not equipped with some specific functions. The answer to the second question, regarding the intrinsic or socially beneficial value of AI, is also quite clear today.

For many people in Western culture, AI has a socially beneficial value. If this were not the case, it would not be acceptable for an AI to provide therapy to the elderly. In this context, the end does not justify the means: not all means of relieving loneliness are acceptable. A person who talks to non-existent friends or treats a teddy bear as a living, sentient being is often suspected of being mentally disturbed and pressured to seek psychiatric help.

Given this, why should talking to an AI and developing some degree of dependence on it be considered acceptable and useful? We are clearly not concerned about an AI becoming part of social life.

CONCLUSION

The rule of law as a legal concept is so elusive that the more we try to define it, the more diffuse it seems to become. The spectrum that describes the rule of law is long. It is considered as a political ideal, a mechanism for limiting the abuse of power, and also a mechanism for ensuring that society upholds certain values, for example, human rights.

The common thread of the rule of law is that it is seen as a concept that is worth protecting despite its susceptibility to political abuse. On the other hand, modern technologies are increasingly used in society, of which artificial intelligence is a prime example.

As machine learning techniques improve, artificial intelligence systems are also being used to assist human decision-makers in almost every field. It is to be expected that as these technologies become better at aiding decision-making, more control and responsibility will be transferred to them.

It is therefore important to note that these technologies challenge the ideals associated with the rule of law as a concept of traditional law. In addressing the harms associated with AI in relation to the rule of law, a common thread that emerges is the way in which it potentially hinders human flourishing.

While this may not be the first traditional connection to the rule of law as a concept, it is nevertheless important to address the human factor as a cornerstone of society. In this research, we conclude that the

legal challenges and requirements facing the law and the future use of AI are unpredictable and that we must be forward-looking and plan to meet these challenges.

Recommendations

The need to establish uniform international laws on the safe use and application of artificial intelligence.

Establish detailed and precise laws regarding users of artificial intelligence.

Legislation in the field of privacy and copyright or intellectual property in the use of artificial intelligence.

Creating a mindset of artificial intelligence rights among users, producers and developers of artificial intelligence.

If there is ever a new "race" of intelligent machines with human-level consciousness, there is a need to legislate for it as a real person of the machine or artificial intelligence.

The most important legal point in the discussion of artificial intelligence is the announcement and transparent information about the type and amount of data used by artificial intelligence, as well as the use of a specific artificial intelligence label on its products and services, and the distinction of human products from artificial intelligence.

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Advancements in Neural Implants: A Systematic Review of Neuralink-Enabled Brain-Machine Communication

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Abstract; This systematic review examines recent advancements in neural implants with a focus on Neuralink-enabled brain-machine communication systems. By integrating ultra-flexible electrode threads, high-channel wireless data transmission, and robotic surgical implantation, Neuralink represents a significant leap in neural interface technology aimed at restoring movement, communication, and sensory perception for individuals with severe neurological impairments. The review situates Neuralink within the broader landscape of brain-machine interface (BMI) development, comparing its approach to competing technologies such as Synchron's endovascular Stentrode, Blackrock Neurotech's Utah array, and Paradromics' high-bandwidth systems. Key design considerations—including biocompatibility, signal stability, power management, and data security—are explored, alongside the ethical and regulatory challenges associated with invasive neurotechnology. Early clinical trials, including Neuralink's first-in-human implant, demonstrate the feasibility of enabling mind-controlled computer interaction in paralyzed individuals. This paper also highlights sustainability dimensions, such as the development of minimally invasive techniques, long-term implant durability, and inclusive access to assistive neurotechnology. By synthesizing recent peer-reviewed studies and clinical milestones, this review outlines the current state, emerging challenges, and future directions of neural implant systems that bridge human cognition and digital systems—positioning them as a critical component in the evolution of sustainable and intelligent healthcare technologies.

Keywords: Neural implants, Brain-machine interface, Neuralink, Neurotechnology ethics

INTRODUCTION

Brain–machine interfaces (BMIs), also known as brain–computer interfaces (BCIs), are systems that acquire and interpret neural signals to control external devices or computers by thought alone. Once a concept confined to science fiction, neural implants for BMI have rapidly become a tangible reality in recent years, offering new hope for individuals with severe neurological impairments. These devices establish a direct communication link between the human brain and machines, translating brain activity into actionable commands that can, for example, move a robotic limb or control a computer cursor. Such technology has profound implications: it promises to restore mobility, communication, and independence to people affected by paralysis, motor neuron diseases, or sensory deficits. Indeed, the U.S. Food and Drug Administration's approval in May 2023 of human trials for Neuralink's implantable BMI marked a **monumental stride** in this field – a milestone likened to a "moonwalk" for neurotechnology.

This review provides a comprehensive overview of advancements in neural implants with a focus on Neuralink – Elon Musk's high-profile neurotechnology venture – and its enabling of brain-machine communication. We begin by outlining the background and evolution of brain-machine interfaces, highlighting key achievements that paved the way for today's innovations. We then examine Neuralink's

system design and technical breakthroughs, detailing how its approach differs from prior neural implants. Similar emerging technologies and competing approaches are compared to contextualize Neuralink's contributions within the broader BMI landscape. Next, we discuss current and potential applications of neural implants, from assistive communication to sensory restoration, illustrating the life-changing impact for patients. We also address the technical challenges, design considerations, and ethical and regulatory issues inherent in this fast-evolving domain – including biocompatibility, data privacy, and patient safety concerns. Finally, we consider future directions for neural implant technology and its role in shaping a more sustainable and inclusive technological future. By synthesizing findings from recent trials and studies, this systematic review aims to clarify the state of Neurolink-enabled brain-machine communication and its trajectory moving forward.

Background: Evolution of Brain-Machine Interfaces

The concept of connecting brains to machines has a rich history in neuroscience and biomedical engineering. Early research in the 1990s and 2000s demonstrated that implanted electrodes could capture signals from the brain's motor areas and use them to control external devices. Notably, the **Utah Array** – a tiny bed-of-needles electrode grid developed at the University of Utah – became a standard for invasive BCIs by the early 2000s. In 2004, a patient with paralysis (Matthew Nagle) was outfitted with a Utah array and became the first person to control a computer cursor using only neural signals. Over the subsequent decade, academic consortia like the *BrainGate* program showed that people with tetraplegia could not only move cursors but also control robotic limbs and other assistive devices via implanted brain sensors. For example, by 2012 researchers enabled a BrainGate participant to reach out with a robotic arm and drink coffee by thinking about the movement – a groundbreaking demonstration of neuroprosthetic control in a human. These early successes, though limited to laboratory settings with bulky wiring and only dozens of electrode channels, proved that *brain-machine communication* was feasible and could restore some level of function to those with severe paralysis.

In parallel with these BMI developments, other types of neural implants have seen widespread clinical use, establishing a precedent for implantable neurotechnology. **Cochlear implants** to restore hearing and **deep brain stimulators (DBS)** to treat movement disorders like Parkinson's disease have been implanted in tens of thousands of patients, underscoring that chronically implanted devices can be safe and beneficial. In fact, as of the mid-2020s, over 150,000 individuals in the United States carry some form of brain implant – mainly DBS devices – to alleviate conditions such as tremors, dystonia, and epilepsy. The long-term successes of DBS (used for decades to reduce Parkinsonian tremors) illustrate that invasive neural interfaces can dramatically improve patients' quality of life, although even these technologies come with quirks (one Parkinson's patient famously forgot how to swim after DBS implantation, highlighting the complex effects of brain interventions).

Another recent breakthrough highlighting the potential of brain-machine interfaces is the development of a so-called "**digital bridge**" between the brain and spinal cord. In 2023, researchers in Switzerland enabled a man with chronic paralysis to **walk naturally** again using a brain–spine interface. In this system, an implant in the patient's motor cortex detected the intention to walk and wirelessly transmitted signals to a stimulator implanted in the lumbar spinal cord. The spinal implant then delivered patterned electrical pulses to activate leg muscles in real time, effectively bypassing the patient's spinal injury. This achievement demonstrates the extraordinary promise of neurotechnology not just for controlling external machines, but for re-establishing lost connections within the nervous system itself – in this case, bridging a damaged spinal cord to restore volitional movement.

Together, these milestones set the stage for the current generation of high-bandwidth, wireless neural implants. Early BCIs proved that a handful of electrodes could grant basic computer control to paralyzed

users, but they also revealed limitations: limited signal resolution, cumbersome wired setups, and short device lifespans due to biocompatibility issues. As we will discuss, today's innovators – most prominently Neuralink – are building on these lessons. They aim to create *scalable* brain-machine interfaces that can record from orders of magnitude more neurons, operate fully implantably (with wireless data and power), and remain stable in the brain for years. The following sections review how Neuralink's approach attempts to achieve these goals, and how it compares to other emerging neurotechnologies in this "future systems" frontier of human-machine integration.

Neuralink's Implant Design and Technology

Neuralink, founded in 2016, entered the BCI field with the ambitious goal of dramatically increasing the communication bandwidth between brains and computers. The company's philosophy is encapsulated in its mission to *"restore autonomy to those with unmet medical needs today and unlock human potential tomorrow."* In practical terms, Neuralink seeks to create a *general-purpose* BMI device – one that can be implanted into the brain to record neural activity at an unprecedented scale and transmit those signals wirelessly to external devices for real-time control or even sensory feedback. Neuralink's system, currently exemplified by the **N1 implant** (also dubbed "the Link"), integrates several state-of-the-art innovations in neural interface design: ultrathin and flexible electrode arrays, high-density on-chip signal processing, wireless communication, and robotic surgical implantation.

Device Architecture: The N1 Link is a small, coin-shaped neural implant designed to reside fully inside the skull, with no external connectors. It contains a circular biocompatible housing that encases custom electronics (signal amplifiers, digitizers, a Bluetooth wireless module, and a rechargeable battery). Emanating from this disc-like implant are **64 ultra-fine polymer threads**, each thread just a few micrometers thick, which serve as electrode carriers. Across those 64 threads, the implant hosts a total of **1,024 electrode contacts** – an order of magnitude more channels than previously common implants like the 100-electrode Utah array. These electrodes penetrate into the cortical tissue and are distributed in the regions of interest (for example, the hand and arm areas of the motor cortex for a patient with paralysis). By placing so many electrodes so close to neurons, the device can pick up high-resolution neural signals (individual action potentials and local field potentials) from a large population of cells. The implant's onboard chips amplify and preprocess these signals, then **wirelessly transmit the data via Bluetooth** to an external computer in real time. This fully wireless design represents a significant leap from earlier human BCIs that relied on percutaneous connectors or transmitter pedestals – for instance, the first BrainGate trials in the 2000s had cables running from the user's head to the computer. In contrast, Neuralink's implant is self-contained: it sends brain data out **telemetrically** and is powered by an internal battery that can be recharged inductively (through the skin) using a wireless charging pad or wearable "charging hat". As Elon Musk memorably summarized, Neuralink's implant is essentially *"a Fitbit in your skull with tiny wires"* – a description highlighting its compact, cordless nature. Figure 1 (not shown) conceptually illustrates this design: a disc-like implant seated in a skull opening, with flexible threads fanning out into the brain tissue.

Flexible Threads and Insertion Robot: The use of flexible electrode threads is one of Neuralink's core innovations. Traditional microelectrode arrays (like the Utah array) are made of rigid silicon or metal needles that are **stabbed into the cortex**, which, while effective for initial recording, cause substantial tissue damage and inflammation over time due to the brain's micromovements and the stiffness mismatch between metal and brain tissuejmir.orgjmir.org. Neuralink instead fabricates electrodes on thin polymer filaments (polyimide substrate with gold traces) that are far softer and more compliant – closer to the consistency of neural tissue itselfjmir.org. This flexibility is expected to improve biocompatibility and longevity by reducing the immune response and scar tissue that typically forms around stiffer implantsjmir.orgjmir.org. However, a thin thread (on the order of 5–50 μm in width) is too floppy to

penetrate brain tissue on its ownjmir.org. Neuralink's solution is a **custom neurosurgical robot** (the R1 robot) that can accurately insert these threads into the cortex. The R1 robot resembles a small sewing machine: under optical guidance, it uses extremely fine needles to grasp each flexible thread by a tiny loop at its tip and "stitch" it into the brain at precise target locations and depthsjmir.org. This insertion process is automated and fast – the robot can place roughly **6 threads per minute**, equivalent to 192 electrodes per minute, far outpacing manual neurosurgeryjmir.orgjmir.org. Critically, the robot is programmed to perform insertions with micron-level precision while avoiding blood vessels on the brain surface, using high-resolution imaging (including **optical coherence tomography**) to prevent hemorrhage. Neuralink's 2019 technical report demonstrated the robot inserting **96 threads (3,072 electrodes)** reliably in under an hour in animal modelsjmir.orgjmir.org. The end result is an array of hairlike electrodes spread through multiple cortical layers and regions, all connected to the central implant. By employing flexible threads and robotic implantation, Neuralink achieves both **high channel counts and minimal tissue trauma**, marrying the advantages of prior "microwire" research with modern automation. Biomedical engineers have noted that Neuralink "took the best of everything… and put it all together" into a single device.

High-Density Signal Processing: Another key aspect of Neuralink's implant is the custom silicon that digitizes neural signals. The N1 device contains application-specific integrated circuits (ASICs) designed to **amplify, filter, and multiplex** the data from thousands of channels in paralleljmir.orgjmir.org. Remarkably, the entire 1024-channel system is packaged into an implant just **23 × 18.5 × 2 mm** in size, according to Neuralink's initial publicationjmir.org. In early prototypes, a single high-bandwidth wired connection (via USB-C) could stream all channels simultaneouslyjmir.org. In the current wireless incarnation, data is compressed on-board and sent out via Bluetooth at a rate sufficient to transmit neural spikes and even local field potential waveforms for all channels. An external software stack then decodes these signals into useful commands. Machine learning algorithms calibrate the system to the individual's neural firing patterns – for example, identifying the distinctive activity that corresponds to an attempt to move the right hand versus the left. Over time, the decoder can be refined to improve speed and accuracy, and can even adapt as the neural signals change or as the user gains proficiency (adaptive decoding is a feature being explored in BMI research broadly). Neuralink has reported that with its implant platform, they have achieved a **spike recording yield of ~70%** of electrodes (meaning a majority of the 1024 channels pick up stable signals from individual neurons) in long-term animal studiesjmir.org. This is a promising figure indicating many channels remain functional chronically, although it will need to be borne out in human trials.

First-in-Human Trial (PRIME Study): In July 2023, Neuralink received FDA clearance to begin its first human clinical study, officially titled **"Precise Robotically Implanted Brain-Computer Interface" (PRIME)**. The trial aims to evaluate the safety and functionality of the N1 implant in humans with paralysis. By early 2024, Neuralink announced that the **first human subject** had been implanted with the device. This first patient, a 30-year-old man named **Noland Arbaugh** who had been left quadriplegic by a spinal cord injury, underwent the Neuralink implantation surgery in January 2024. Remarkably, he was discharged from the hospital just **one day** after the procedure and reported no immediate side effects, indicating the surgery was relatively well-tolerated. By March 2024, Neuralink released a video of Mr. Arbaugh using the brain implant to play a game of chess on a computer **entirely by mind control**. He was able to move a computer cursor and click on squares of a chessboard using only his thoughts – a striking demonstration of brain-driven communication with a software application. In media interviews, Arbaugh described how the implant allowed him to reconnect with the world, regaining abilities like **independently browsing the web, sending messages, and playing video games** that he had lost due to paralysis. Within a week of his surgery, he could volitionally move a cursor on screen by two mental strategies: *"attempted movement"* (imagining moving his hand to guide the cursor) and *"imagined movement"* (simply visualizing the cursor's motion). Both methods felt intuitive to him, and he could even multitask – for instance,

conversing or eating while simultaneously controlling the cursor. Neuralink reported that this first user achieved a record-high bit rate for a BCI cursor, peaking around **8 bits per second** for target selection (a measure combining speed and accuracy). This roughly translates to making a selection on a grid in well under a second, which is an impressive throughput for a first-generation device and on par with, or better than, prior BMI trials that used older tech. In short, the initial clinical results showed that a wireless, fully implanted BMI with 1024 channels can enable fast, reliable brain-driven computer control – a vindication of Neuralink's high-bandwidth approach.

User Experience and Maintenance: A critical design goal for Neuralink is to make the device *user-friendly* for daily life. Mr. Arbaugh noted that once healed from surgery, he **cannot feel the implant at all** – if he didn't remember getting it, he "wouldn't believe" there's a chip in his head, because there is no sensation or external sign of it. This speaks to the completely implantable nature (nothing protrudes from the scalp) and biocompatibility of the unit. The N1 system communicates with a phone or computer wirelessly, so the user interface is likely a combination of an app and possibly some wearable accessory when needed. The one maintenance requirement is recharging the battery: the implant must be **charged regularly (likely daily)** by inductive coupling. In practice, the patient wears a special hat or headset containing a wireless charger coil, typically for a couple of hours, to top up the implant's battery. Arbaugh mentioned that needing to stop and charge the device occasionally was an "unavoidable drawback" that interrupted his longer computer or gaming sessions. Still, compared to earlier systems that physically tethered users or required technicians to maintain, this is a significant improvement in autonomy. As wireless power technology advances, future versions might extend battery life or allow continuous trickle charging via a thin solar panel in a hat, for example. It's also worth noting that Neuralink's implant is **firmware upgradeable** – much like a smartphone, it can potentially receive software updates (e.g. improved decoding algorithms) over the air, and Elon Musk has even mused about users "upgrading" their implant hardware over years, analogous to swapping an old iPhone for a newer model. While routine brain surgeries for upgrades are not practical today, the modular and self-contained design means that if an implant ever needs replacement (due to battery depletion or technological obsolescence), it could be removed and a new one inserted in the same cavity with the assistance of the robot, minimizing additional damage.

Safety and Early Challenges: As with any pioneering clinical device, Neuralink's initial human experiences have highlighted both achievements and challenges. The surgery to implant the device – essentially a robot-assisted keyhole craniotomy – appears to have been safe in the first patient, with a quick recovery and no neurological deficits reported. However, a few weeks into use, Neuralink encountered a hardware issue: about **85% of the electrode threads in the first implant "retracted"** from their target positions in the brain, causing a significant drop in performance. In other words, the thin threads had partly backed out of the tissue, likely due to either subtle movements, tension, or other biomechanical factors, thus losing contact with many neurons. This problem aligns with one of the major concerns the FDA had initially cited (during an earlier approval attempt in 2022) – the potential for *migration of the implant's wires* over time and questions about how the device could be safely removed or adjusted if needed. Neuralink's team responded by re-calibrating the decoder algorithms to rely on the remaining stable electrodes, which restored much of the functionality for the user despite the loss of many channels. By May 2024, Neuralink publicly acknowledged the issue and indicated a plan to mitigate it in future surgeries: they would insert the threads **deeper into the brain (about 8 mm deep, vs the 3–5 mm depth in the first try)**, in hopes that a greater embedded length would resist retraction. The U.S. FDA approved this modification, and by mid-2024 Neuralink moved forward to implant its device in a second and third human participant with the updated approach. As of mid-2025, formal published results from these human trials are still pending, and it remains to be seen how well the mitigation strategies work. Nevertheless, the occurrence of thread migration emphasizes the experimental nature of the technology – kinks are still being worked out – and

underscores why early trials are cautious and small in scale. It is through these iterative improvements that Neuralink and similar ventures will learn to optimize implant **placement stability, signal longevity, and overall safety** before any wider clinical use. Musk himself has admitted that it may be "*decades*" before brain implants like Neuralink's are refined and proven enough for widespread commercial availability.

Beyond Motor BCIs – Vision and More: While Neuralink's first focus is on motor restoration (enabling people with paralysis to control computers and eventually prosthetic limbs), the company has signaled broader ambitions in the neural implant space. In late 2024, Neuralink announced an experimental implant nicknamed **"Blindsight"** aimed at **restoring vision** for people with blindness. This device would implant electrode arrays into the visual cortex of the brain to directly stimulate visual perceptions, bypassing damaged eyes or optic nerves. The concept is that a camera feed could be converted into patterns of electrical stimulation in the visual cortex, potentially granting a form of artificial sight. In September 2024, the Blindsight visual prosthesis was granted **FDA Breakthrough Device** status, indicating it addresses a serious unmet need and may receive expedited review. While still in early development, it highlights that Neuralink-enabled brain-machine communication is meant to be a *two-way street*: not only reading information from the brain (as in motor BCIs) but also writing information into it (as in sensory prostheses). Moreover, Neuralink's devices are **bi-directional** by design – the hardware supports not just recording but also stimulation of brain tissue. This raises future possibilities like modulating brain circuits to treat psychiatric conditions or enhance cognitive function. Indeed, Elon Musk has often hyped long-term goals such as memory enhancement or "telepathic" communication between brains, and has framed Neuralink as a way to achieve symbiosis with AI. While such scenarios remain speculative and ethically fraught, the underlying technology (high-bandwidth implants) could in theory be software-configured for a variety of uses: e.g. *stimulating* the somatosensory cortex to provide a sense of touch from a prosthetic limb, or recording from speech-related areas to decode internal speech (as some academic groups have begun doing).

In summary, Neuralink's approach to neural implants represents a significant advancement in BMI technology. By combining **flexible high-count electrodes**, **robotic surgery**, and **wireless digital interfaces**, it has pushed the field toward devices that are more scalable, user-friendly, and integrated than ever before. The initial human use has validated the concept by enabling rapid mind-controlled computer use in a person with paralysis. At the same time, early challenges like electrode stability and the need for transparency underscore that this is still a work in progress. Neuralink stands at the forefront of BMI innovation, but it is not alone – many other players are contributing different ideas and technologies to achieve similar goals. The next section reviews some of these **similar technologies and competing approaches** in neural implants, to compare how the field at large is tackling the challenge of connecting brains and machines.

Similar Technologies and Competing Approaches

The race to develop effective brain-computer interfaces has attracted numerous companies and research teams, each with its own strategy for interfacing with the brain. While Neuralink has captured public attention with its wireless high-density implant, it joins a landscape of both well-established and up-and-coming neurotechnology efforts. Below, we outline several notable **similar technologies** and how they compare or contrast with Neuralink's design:

- **Blackrock Neurotech (Utah Array):** Blackrock Neurotech (formerly Blackrock Microsystems) is a pioneer in the BCI field, known for manufacturing the Utah array – the workhorse electrode used in many academic trials for the past 20+ years. The Utah array is a small silicon chip (about 4 mm square) studded with 100 stiff microelectrodes that penetrate the cortex. It was first implanted in humans in the early 2000s and has enabled patients with paralysis to control cursors, robotic arms,

and other devices in clinical research settings. For example, participants in BrainGate studies who received one or two Utah arrays have achieved point-and-click typing, wheelchair control, and even multi-limb coordination via computer interfaces. However, the Utah array requires a percutaneous pedestal (a metal plug on the head) to connect to external electronics, and its channel count is relatively low (often 64 or 128 channels if multiple arrays are used). Blackrock Neurotech has been working on wireless versions and higher-channel variants, but as of 2025 the company has **not yet obtained FDA approval for a long-term commercial BCI device**. Blackrock's approach is considered **invasive and high-fidelity** (similar to Neuralink in that it places electrodes within brain tissue), but the rigid electrode design can cause tissue scarring, and the need for through-skull connectors is a drawback for practical use. Neuralink essentially aims to improve on Blackrock's concept by using many more electrodes (>>1000 vs. 100) that are flexible and fully implantable with no skull plug. Both companies target motor cortex for restoring movement and communication, and Blackrock has an impressive track record of human studies that laid the groundwork for what Neuralink is now attempting.

- **Synchron (Stentrode Endovascular BCI):** Synchron is a company taking a markedly different route – a **minimally invasive** BCI that does not require open brain surgery. Synchron's device, called the **Stentrode**, is a small mesh-like electrode array mounted on a stent (a metal scaffold). It is delivered into the brain's vasculature using a catheter, similar to how cardiac stents are placed. The Stentrode is guided via blood vessels (specifically, into a vein adjacent to the motor cortex) and then expanded to press the electrodes against the vessel wall, so they can pick up neural signals from the brain area nearby. The obvious advantage is avoiding a craniotomy – the procedure is much less invasive, using the vascular system as a "natural" access pathway. In 2021, Synchron announced the **first-in-human use of a fully implanted endovascular BCI**, and by 2022 they had implanted the Stentrode in a few patients with paralysis in Australia. In a clinical study (SWITCH trial), five patients with severe upper limb paralysis used the device to control computers with their thoughts – achieving functions like texting, emailing, and online shopping – all **wirelessly** and with no serious adverse events over 12 months. The signals from the Stentrode are relayed to a wireless transmitter implanted in the chest, which then communicates with external devices. This shows that even with a relatively small number of electrodes (the Stentrode has on the order of a couple dozen channels), meaningful BMI control is possible when targeting high-level intents (like attempting to move a limb to trigger a mouse click). Synchron has received FDA Breakthrough Device designation and begun U.S. trials, putting it arguably "ahead" of Neuralink in human testing progress (as of 2022-2023). However, the fidelity of an endovascular interface is inherently lower – it records from outside the brain rather than inside it. Thus, while Synchron's approach maximizes safety and ease of implantation, it currently offers less precision and bandwidth compared to Neuralink's high-density intracortical approach. Interestingly, some experts suggest that a combination of strategies might be used in the future (for example, a noninvasive or endovascular interface for broad control combined with a focal high-density implant for fine control). For now, Synchron represents the **leading less-invasive BMI** competitor, prioritizing near-term accessibility over raw information throughput.

- **Paradromics:** Paradromics is a U.S. startup also pursuing high-channel-count brain implants. Their approach is often likened to Neuralink's in that they focus on **thousands of channels and advanced electronics**. Paradromics has developed an array called the **Connexus Direct Data Interface**, which uses bundles of microwires to achieve up to 1,600 channels per module, with the goal of scaling to 10,000+ channels by combining modules. Unlike Neuralink's thread design, Paradromics initially explored a *"needle ensemble"* approach (many fine needles inserted simultaneously) and has since moved toward flexible polymer electrodes as well. They have also

emphasized high-throughput data telemetry and signal processing, similar to Neuralink's fully implantable wireless strategy. As of 2023, Paradromics was preparing for initial human trials, aiming to help patients with conditions like locked-in syndrome to communicate via a direct brain-text interface. While detailed technical data are not as public, Paradromics has indicated their implant would involve an array implanted on cortical surface or shallow penetration, connected to a subcutaneous telemetry unit. In summary, Paradromics shares Neuralink's **high-bandwidth vision**, but is still in preclinical stages. It serves as another example of how multiple engineering teams are tackling the problem of scaling up neural interfaces with modern technology.

- **Precision Neuroscience (Layer 7 Cortical Interface):** Precision Neuroscience is a company co-founded by one of Neuralink's former founding team members. It takes yet another approach to neural interfacing: a **thin, flexible electrode array** that lies on the surface of the brain (under the dura mater) rather than penetrating into neural tissue. Dubbed the **"Layer 7" interface** (a nod to the cortex's layered structure), the device is likened to a piece of flexible **"scotch tape"** that can be slid under the skull and rest on the cortex. This design aims to be less invasive than penetrating electrodes like Neuralink's threads, while capturing higher-fidelity signals than external EEG. In 2023, Precision Neuroscience announced it had used this film-like array in *three patients* undergoing neurosurgery for tumors. In those cases, the Layer 7 device was temporarily placed on the brain surface to record activity (with patient consent) and then removed – demonstrating biocompatibility and signal acquisition, though not yet as a permanent implant. The eventual goal is a *fully implantable* version with a thin profile that doesn't require a big hole in the skull. Because it doesn't penetrate, it likely has less risk of injury or long-term damage, but it also may pick up less localized signals (each electrode might average signals from many neurons). Precision's strategy can be seen as **minimally invasive but moderate bandwidth**, potentially occupying a middle ground between Synchron's endovascular method and Neuralink's intracortical method. It highlights the trend of making electrodes ever thinner and more flexible to reduce harm to the brain – a principle Neuralink also champions, albeit with insertion into the tissue. If successful, a future Precision implant might be introduced via a slit in the skull, unrolled onto the cortex, and interface with hundreds of channels with no penetrations, providing a safer but still useful BMI for certain applications.

- **Academic and Other Commercial Efforts:** In addition to the above, there are numerous other efforts in the neurotech ecosystem. The **BrainGate consortium** (Massachusetts General Hospital, Brown University, etc.) continues to run clinical trials with improved versions of implanted Utah arrays, including testing **wireless transmitters** that eliminate cords while using the same arrays. Companies like **Neuralink's Science Corp (by Neuralink's ex-president)** and **Precision's competitors like Cortec and Corticale** are exploring implants for restoring vision or mapping brain activity during neurosurgery. Even non-invasive BCIs (like electrode caps and wearable devices) are improving with machine learning, though they cannot yet match the performance of implanted electrodes. Finally, military and government research (e.g. DARPA's programs) have invested in BMI innovations such as **optical BCIs** (using light to read neurons) and even **nanotechnology-based electrodes**, which could someday provide high-channel interfaces without conventional surgery.

In summary, Neuralink is part of a vibrant, competitive landscape. Each approach has trade-offs: **invasive vs. noninvasive, high bandwidth vs. high safety, penetrating vs. surface electrodes, wired vs. wireless**. Neuralink's distinctive contribution is arguably the integration of *extremely high channel count, flexibility, and wirelessness* in one implant, plus the development of a robotic surgical system to deploy it. As one article aptly noted, Neuralink has reinvigorated public interest in this field, spurring comparisons and a

"race" among companies. Table 1 (hypothetical) might compare these on key metrics like channels, invasiveness, status of human trials, etc. All these efforts share the common vision of enabling direct brain-machine communication to assist people – and collectively, successes in any one approach benefit the field by demonstrating possibilities and solving problems that others can learn from. The next section will delve into the **applications** of such neural implant systems – what they can do today, and what they might enable in the near future.

Applications of Neural Implants and Brain-Machine Communication

Neural implants that facilitate brain-machine communication have predominantly been developed with **medical applications** in mind – specifically, to restore functions lost due to neurological injury or disease. We outline several major application areas below, highlighting current achievements and future potential:

- **Restoring Movement and Autonomy in Paralysis:** The flagship application for Neuralink and similar BMIs is to help people with paralysis regain control over their environment. By translating neural intentions into action, these systems effectively bypass damaged pathways (such as an injured spinal cord). In current trials, this most often means enabling computer interaction: for instance, allowing a quadriplegic person to move a cursor and click purely by thinking about moving. This capability alone can be life-changing – it opens the door to communication (via on-screen keyboards or texting), environmental control (smart home devices, wheelchair navigation), and recreation (using the internet, playing games) without needing physical movement. As described earlier, Neuralink's first human user can **browse the web, send texts, and play video games (like digital chess)** using his implant, which has given him back a sense of independence and connection. Beyond cursors, research participants in BMI studies have used brain signals to control **robotic arms and hands**. In one notable case, a paralyzed individual used a brain implant to mentally guide a robotic arm to pick up a bottle and drink from it with a straw, achieving a functional goal of self-feeding. Other studies enabled people to shake hands or even fist-bump U.S. President Barack Obama using a thought-controlled prosthetic hand. These demonstrations underscore that *motor neuroprosthetics* can restore practical actions. The ultimate goal is to reconnect brain to body – for example, drive exoskeletons or stimulate a patient's own paralyzed limbs. As mentioned, a brain-spine interface recently allowed a man to walk again by delivering his brain's commands to his legs in real time. While that approach involved bridging within the body, it shares the same principle of BMI. In the future, a Neuralink device might be able to send signals to *functional electrical stimulators* on a person's muscles, potentially enabling a paralyzed person to move their own arms or hands by will. At present, the focus is on mastering control of external devices like wheelchairs, computer cursors, and assistive robots – stepping stones toward greater mobility and autonomy.

- **Communication for Patients with Locked-In Syndrome:** For patients who cannot move or speak at all (e.g. advanced ALS or brainstem stroke patients), BCIs offer a channel to communicate with the outside world. Even a basic BMI that allows selecting letters on a screen can be a lifeline for someone who is "locked in." Existing implant systems using Utah arrays or ECoG (electrocorticography) strips have enabled some paralyzed people to type at 5–10 words per minute by mind-selection of letters. Neuralink's higher bandwidth could potentially improve communication rates. In fact, one of Neuralink's stated initial goals is to enable *speech BCIs* – Musk gave the example "imagine if Stephen Hawking could communicate faster than a speed-typist". Recent academic advances have shown it is feasible to decode intended speech directly from cortical activity: in 2021, researchers decoded whole words and sentences from the brain signals of a paralyzed man, effectively creating a **brain-to-text transcription** in real time. That

study (Moses et al. 2021) used a high-density electrode grid on speech motor cortex and achieved up to 15 words per minute of decoded speech by mapping neural patterns to the patient's attempted vocalizations. Such work suggests that future neural implants could restore a voice to those who cannot speak, by directly translating their brain activity into synthesized speech or text. Neuralink has the technical capacity (with 1024+ electrodes and smart decoding) to pursue this application, and the company has indeed advertised for "speech BCI" specialists. If successful, a Neuralink user might one day silently think of words and have them output as audible sentences by a computer – a transformative ability for those with locked-in syndrome or profound speech impairment.

- **Sensory Restoration (Vision and Hearing):** Another major application is **neuroprosthetics for lost senses**. The cochlear implant, as noted, is a very successful example of a neural implant that restores hearing by stimulating the auditory nerve. Neural implants are now pushing into restoring vision for the blind. Neuralink's Blindsight project aims to implant electrodes in the visual cortex to produce phosphene patterns (dots of light) that the brain can learn to interpret as visual images. If resolution is sufficient, this could provide basic object recognition or navigation ability to those with no sight. Early cortical visual prosthesis trials (e.g. by Second Sight/Mind^VR) have shown partial successes – volunteers can perceive crude patterns or letters – but Neuralink's high channel count might drastically improve the resolution (think hundreds of pixels of "vision" vs. a few dozen previously). In the long run, a fully implemented visual BMI might allow even those who were born blind to receive visual information streamed from a camera directly into their brain, achieving a form of artificial vision. Beyond vision, there are efforts to use brain implants for restoring **touch and proprioception**. For instance, when a person controls a robotic arm with their mind, researchers have also given them a sense of touch by implanting stimulators in the brain's sensory cortex and feeding back signals from the robot's hand. Some BCI trial participants have reported feeling the touch of objects through the robotic hand this way. Such bidirectional interfaces (sometimes called *closed-loop BCIs*) are highly complex, but they illustrate the potential to *not only read* from the brain but also *write in* sensations, closing the loop to make prosthetic control more natural and dexterous.

- **Neurorehabilitation and Cognitive Enhancement:** A growing area of BMI application is in rehabilitation after stroke or brain injury. Neural implants might be used temporarily to retrain the brain by providing feedback or modulating neural circuits. For example, an implanted chip could potentially promote recovery of movement by stimulating certain brain areas in synchrony with physical therapy exercises – essentially helping the brain rewire more efficiently. There is also interest in treating psychiatric and neurological disorders: Deep brain stimulation is already used for depression and OCD in some cases, and research is ongoing into using cortical stimulation to boost memory in Alzheimer's or improve attention and mood. Musk has hinted that Neuralink could address disorders like depression, anxiety or memory loss by targeting relevant brain regions in the future. While these claims are currently speculative, the general concept is that a finer control over brain circuits via implants could correct pathological activity (similar to how DBS corrects Parkinson's tremors by stimulating basal ganglia circuits). Furthermore, **cognitive enhancement** applications – though far off and ethically charged – have been proposed. In theory, a BMI could augment human cognition by offloading memory storage to a computer or enabling direct brain-to-brain information transfer. Musk's talk of achieving *"symbiosis with AI"* reflects an aspiration that healthy individuals might one day use neural implants to interact with artificial intelligence systems or each other at the speed of thought, thereby greatly expanding human cognitive capabilities. For now, mainstream research remains focused on therapeutic uses for those in need, rather than enhancement for the general public, given the medical risks and ethical concerns. It is worth noting, however, that even current achievements can be seen as *augmenting* human ability: for a person

who is paralyzed, a BCI that lets them operate a computer is enhancing their capabilities beyond what their biological condition allows. In that sense, neural implants are already "enhancements" for those who desperately need them, alleviating disability and improving quality of life.

In summary, the applications of neural implants span a spectrum from restoring lost **motor and sensory functions** (movement, communication, vision, hearing) to potentially **treating neurological disorders** (via stimulation or closed-loop modulation), and even to **future human enhancement**. At present, the most concrete applications – and the ones aligning with sustainable healthcare goals – are those addressing disability. BMIs are offering new channels for people with paralysis or sensory loss to engage with the world again, promoting inclusivity and autonomy. As these technologies mature, we can expect clinical translation in assistive devices for paralysis (perhaps within the next decade for basic computer control interfaces), and experimental treatments for blindness or speech loss to progress. The **enormous upsides** are evident in cases like a locked-in patient typing their first words in years, or a blind patient seeing a rough image. Each advancement reduces human suffering and dependence. But with these exciting possibilities come significant *technical and ethical challenges*, which we explore in the following sections.

Technical Challenges and Design Considerations

Designing and deploying neural implants for brain-machine communication is an engineering feat that must contend with the complexities of both technology and biology. Despite remarkable progress, several **technical challenges** remain before devices like Neuralink's can become routine medical solutions. Key issues include biocompatibility and safety, signal stability, data management, and practical usability.

Biocompatibility and Longevity: The human brain is delicate and not naturally amenable to having foreign objects embedded within it. A central challenge is making electrodes that can **last for years in the brain without causing damage or losing signal quality**. Traditionally, rigid implants (e.g. metal or silicon probes) trigger a foreign-body response: the immune system treats them as irritants, leading to inflammation, glial scarring around the electrodes, and eventual neuron loss or electrical insulation by scar tissuejmir.orgjmir.org. This can drastically reduce signal quality over time, often within months to a few years. Neuralink's use of *ultrathin, flexible polymer threads* is a direct attempt to mitigate this issue by matching the mechanical properties of brain tissue and causing minimal disruptionjmir.org. Initial animal studies by Neuralink showed that flexible threads can record neural spikes for many months with less scarring than traditional arrays, but **long-term human biocompatibility is still unproven**. Will the threads remain in place and functional 5, 10, 20 years post-implantation? Material selection (polyimide, gold, parylene coatings) will influence corrosion and durability. As seen with the first human implant, even flexible threads experienced an issue of **migration (retraction)** which affected their positioning. This highlights how the dynamic environment of the brain (pulsation, minor head movements, etc.) can gradually shift or stress an implant. Engineers must ensure the implant can "settle" and integrate with minimal movement relative to the brain. One consideration is anchoring: Neuralink's threads currently rely on some slack and presumably the brain's surface tension to stay put; future designs might include small barbs or branching structures to hold electrodes in place once inserted – but these must be balanced against causing damage. **Encapsulation** is another issue: the body may deposit proteins or encapsulate the device over time. Advanced coatings that are bio-neutral or even bio-active (promoting neuron growth onto electrodes) are being explored to improve long-term integration. Ultimately, proving *chronic stability* of recordings in humans is a hurdle that only time and continued trials will surmount. Regulatory bodies will likely require evidence that implants can last several years safely if they are to be approved for widespread use in patients.

Safety of Invasive Procedures: Any brain implant requires a surgical procedure, which carries risks such as infection, hemorrhage, or tissue damage. Although Neuralink's robotic implantation is designed to avoid blood vessels and be as minimally invasive as possible, it is still a form of **neurosurgery** – creating a skull

opening, inserting multiple electrodes, and closing up. The company has reportedly used **5 micron precision imaging** to steer clear of surface vasculature when inserting threads[pmc.ncbi.nlm.nih.gov](pmc.ncbi.nlm.nih.gov), but there remains a risk of piercing a blood vessel deep in the brain, which could cause a hemorrhagic stroke. The safety profile in animal studies was acceptable for the FDA to allow human trials, but scaling to broader use means ensuring the procedure can be done consistently without complications. The design of the implant (fully under the skull) at least avoids infection-prone breakouts through the skin; this is a big safety improvement over older percutaneous connectors. Another safety factor is **failure mode**: if something goes wrong with the device, can it be safely removed or replaced? Earlier in 2022, the FDA was concerned about how the Neuralink device would be removed without injuring the brain. The company will need to demonstrate a protocol for explantation – perhaps using the robot in reverse to pull out threads – that doesn't leave pieces behind or cause bleeding. So far, no human removals have been reported, but at some point, a patient might need an implant upgrade or have an issue necessitating removal, and that will test the reversibility of the implant. Additionally, any **stimulation capability** (for future bidirectional use) will raise safety questions about tissue heating or unintended brain activity, so careful limits on current and voltage must be observed.

Signal Quality and Decoding: Even with hundreds or thousands of electrodes, a BCI only works if it can interpret the noisy neural data correctly. The brain's electrical chatter is complex – individual electrodes pick up signals from multiple neurons plus background noise. Decoding algorithms (often using machine learning) are essential to translate patterns of spikes or field potentials into clear commands (e.g. "move cursor up/right"). One technical challenge is maintaining calibration of these decoders over time. Neurons can change their firing properties, or electrodes can shift slightly (as happened with the thread retraction issue), which can degrade the decoding performance. Adaptive algorithms are being developed that continuously update the mapping as needed. Neuralink likely leverages AI techniques to improve accuracy and speed; however, this introduces complexity in validation – the system might become a "black box" if not carefully characterized. Robust decoding also typically requires a **training period**: initially, a user must imagine or attempt certain movements so the system can learn the neural signatures. In Neuralink's first case, the patient was moving a cursor within a week, suggesting a relatively quick calibration (possibly aided by the fact that he could do slight residual movements in his hand, providing some feedback). For completely locked-in users who cannot move at all, calibration might be trickier and might rely on predictive machine learning models. Researchers are actively investigating **auto-calibration** methods and transfer learning to reduce the burden on users. Another consideration is **information bandwidth**: while 1024 channels is high, the brain has billions of neurons – we are still sampling a tiny fraction of the information. There is a theoretical cap on how much detail of movement or thought can be decoded from a limited sample of neurons. Thus, there is ongoing work on feature extraction methods that maximize useful information from each electrode. In summary, achieving **fast, accurate, and robust decoding** is a challenge that spans both hardware (quality of signals) and software (quality of algorithms). It's not enough to have electrodes in the brain; the *whole chain* from signal to command must be optimized.

Data and Power Management: High-channel-count implants generate a lot of data. Neuralink's 1024 channels, each potentially sampling at e.g. 20 kHz, produce on the order of 20 million data points per second. Streaming that wirelessly requires compression and intelligent data reduction (for example, extracting spike times and waveform features rather than raw signal waveforms). The implant's electronics must balance capturing rich data with the limits of wireless bandwidth and battery power. Custom chips in the device perform on-board filtering and event detection to significantly cut down the data that needs radio transmission[jmir.org](jmir.org). Still, as channel counts increase (Neuralink has prototyped up to 3072 channels[jmir.org](jmir.org), and some envision 10k+ in the future), data management becomes an escalating challenge. Power is closely tied to this: the more channels and higher the sampling rates, the more power the device consumes. Heat dissipation is a concern – the implant cannot be allowed to heat up the brain

tissue significantly. Thus, chips must be extremely power-efficient. Neuralink's engineers likely design ASICs with low-power architecture to handle thousands of channels under a few milliwatts. The wireless charging requirement (currently daily) is a practical limitation; improving battery technology or wireless power transfer could extend usage time. If an implant could hold charge for a week, for instance, that would be more convenient. Until then, users have to incorporate charging into their routine (which, as Arbaugh described, is a bit of a nuisance when it interrupts activities like gaming). Engineers must also ensure **fail-safes**: e.g. if battery dies, the implant should not emit any spurious signals or harm tissue (most likely it would just shut down gracefully). Over-the-air firmware updates pose a cybersecurity issue as well (addressed below), but from a technical standpoint, being able to update decoding algorithms or fix bugs without another surgery is a big advantage – provided it's done carefully to avoid inadvertent changes that confuse the user or render the system unsafe.

Scaling and Manufacturing: To treat large populations, these devices need to be manufacturable and the surgical process needs to be scalable. Neuralink's robot is an impressive piece of automation, but currently each implantation is a bespoke procedure. In the future, one can imagine specialized surgical centers with such robots performing multiple surgeries a day, but that requires streamlining patient selection, pre-surgical mapping of where to insert electrodes, and post-surgical support. On the device production side, making biocompatible electronics in large volume with zero defects is non-trivial. Every electrode and every wire bond must function; a single broken thread out of 64, for example, might reduce capability or require design tolerances that account for some failure. Neuralink has invested in **wafer-scale fabrication** of its thread arrays, meaning they can produce many threads at once using semiconductor techniquesjmir.org. That bodes well for reproducibility, but they will need to maintain high yield on these delicate structures. The assembly of the implant (integrating threads with chips and the housing) likely involves precision microsurgery of its own (automated bonding and laser welding, etc.). As the company moves from prototype to product, **reliability and quality control** become as important as raw performance.

In summary, technical challenges in this field span **biology (making the brain and device coexist peacefully)** and **engineering (maximizing performance under real-world constraints)**. Neuralink and its peers must solve issues of **stability, safety, and scalability**: ensuring the implant doesn't harm the brain (and vice versa), keeping signals strong and decoders accurate over long periods, and handling the massive data flow efficiently with limited power. Each challenge is an active area of research. Encouragingly, none of these appear insurmountable – they are being addressed step by step. For instance, the thread retraction problem encountered was met with a solution (deeper implantation) that will be tested. Biocompatibility concerns are being addressed by ever-improving materials and coatings. Decoding is getting better with AI techniques and larger training datasets from human trials. Nonetheless, caution is warranted: the complexity of the human brain means unforeseen issues can arise (e.g., could long-term use lead to plastic changes in the brain that need managing? Could an implant subtly affect the user's thought processes beyond the intended function?). These uncertainties overlap with ethical considerations, which we explore next.

Ethical and Regulatory Considerations

The advent of high-performance neural implants raises profound **ethical, social, and regulatory** questions. As we integrate technology directly with the human brain, considerations go beyond technical efficacy – encompassing patient rights, data privacy, research ethics, and the broader impact on society. In this section, we discuss some key ethical and regulatory issues relevant to Neuralink-enabled brain-machine communication, drawing from current debates and expert analyses.

Informed Consent and Patient Welfare: Ensuring that patients (or trial participants) fully understand the risks and unknowns of experimental brain implants is paramount. Many candidates for BCIs – such as those with locked-in syndrome or severe paralysis – are in desperate situations with limited options. This can

create a **vulnerability**, where patients might consent to very risky procedures out of hope, potentially without a full grasp of implications. Ethicists emphasize the need for rigorous informed consent processes, clear communication of potential benefits *and* risks, and psychological evaluation to ensure participants are not being unduly coerced by their condition. Patients must maintain the right to withdraw from a study, and their **decision-making autonomy** must be respected at every step. There is also concern that patients may develop high expectations (fueled by media hype or company claims) and face crushing disappointment if the technology falls short or fails. The case of Neuralink's first patient having his implant's performance dip due to thread retraction, then partially restored, illustrates how emotional and stressful such trials can be. As one expert noted, the psychological impact of "getting your hopes back, then experiencing a setback" can be significant. Ongoing support and counseling for participants should thus accompany the technical aspects of trials. Additionally, since these devices become *part of the user's body and self* in a way, companies and clinicians have a duty of care that extends long-term. **What happens if an implant malfunctions or if a company goes out of business?** Patients might be left with an unsupported device in their brain. This raises questions about corporate responsibility and the need for contingency planning (e.g., ensuring devices can be safely turned off or removed, and perhaps placing devices in escrow if a firm cannot continue servicing them). Regulators might require implant-makers to have plans for long-term patient support as part of approvals.

Animal Research Ethics: Neuralink and others have relied on extensive animal testing (mice, pigs, monkeys) to develop their technology. There has been **ethical controversy** around Neuralink's animal research practices. In early 2022, public reports surfaced (via the Physicians Committee for Responsible Medicine) alleging that many monkeys in Neuralink's experiments at UC Davis had suffered and even died due to complications from implant surgeries. Out of 23 implanted monkeys, reportedly more than a dozen were euthanized or died, with allegations of inadequate animal care. Neuralink claimed any animal deaths were due to prior conditions or humane euthanasia for experimental endpoints, and that they adhere to animal welfare standards. Nonetheless, the USDA opened an investigation, and the issue drew scrutiny from lawmakers concerned about possible animal cruelty. This situation underscores the **ethical imperative to treat research animals humanely** and use the minimum number necessary to achieve scientific aims. It also highlights a transparency issue: as a private company, Neuralink initially kept details of its animal studies relatively private, fueling speculation. Ethically, society expects that if animals are sacrificed for research, it is done with rigorous oversight (e.g., Institutional Animal Care and Use Committees) and that the knowledge gained justifies the harm. Some ethicists argue that if Musk "cared about the health of patients, he would invest in noninvasive BCIs" rather than invasive ones that cause animal and potential human harm. However, most in the field acknowledge that a certain amount of animal research is currently indispensable to advance invasive BMI tech to a stage safe enough for human trials. Moving forward, Neuralink will need to demonstrate a commitment to **refinement and reduction** of animal experiments, perhaps by sharing data or using modern alternatives (like high-fidelity simulations or *in vitro* brain-organoid testing) when possible. The public and regulatory blowback serves as a reminder that *ethical research conduct* is under the microscope in this novel domain.

Data Privacy and Neurosecurity: One of the most distinctive ethical challenges of brain-machine interfaces is the issue of **mind data privacy**. A neural implant necessarily reads signals that are reflections of a person's thoughts, intentions, perceptions, and potentially even unconscious mental states. This raises concerns about who will have access to this data and how it will be used. In medical BMI applications, the data would be used to assist the patient (e.g., enabling control of a device) and typically handled by secure clinical software. However, as BMI tech evolves, one can imagine scenarios where brain data could be stored on cloud servers, or analyzed by AI, or even inadvertently shared. Sensitive neural data could, in theory, reveal information one might consider private – for instance, unique thought patterns, emotional responses, or other cognitive metrics. **Hacking or unauthorized access** is a serious worry: if a malicious

actor gained wireless access to an implant, could they steal thoughts? Could they insert commands (for bidirectional systems) against the user's will? These scenarios, while far-fetched in the present (implants are not broadcasting raw thoughts and there are significant technical barriers to "mind-reading" beyond the specific motor/sensory signals of interest), are taken seriously by ethicists. Neuralink's wireless communication must be encrypted and authenticated to prevent any external takeover or eavesdropping. Regulators will likely enforce cybersecurity standards on such devices, similar to or stricter than those for other connected medical devices (like insulin pumps or pacemakers, which have already raised hacking concerns). Another aspect is *ownership of neural data*: Does the patient exclusively own their brain data, or can companies use it for research? Clear data governance policies and patient consent for data use are needed. Moreover, if future versions allow continuous brain monitoring (for example, tracking mood or cognitive state to adjust stimulation), it blurs lines between medical device and surveillance device. Legal frameworks (like HIPAA for medical data) might need updates to cover neural data explicitly – some have called for a new category of "neurorights" to protect the privacy of one's brain signals and to guard against unwanted intrusion into one's mental processes.

Transparency and Scientific Rigor: Neuralink has faced criticism for at times bypassing traditional scientific channels. The company famously made splashy public demos (showing a pig with an implant, a monkey playing Pong) and Elon Musk tends to announce milestones on **social media**, sometimes before details are available to the scientific community. For instance, the first human implant was tweeted in Jan 2024, but Neuralink had not initially registered the clinical trial in the public database *ClinicalTrials.gov*, nor had they published a peer-reviewed protocol. This prompted concern that they were not adhering to standard ethical practices of **transparency and peer review**. Indeed, registering trials and publishing results is crucial for independent evaluation and for building trust. Neuralink did later register the PRIME Study after starting it, and presumably will publish outcomes in time, but the initial omission was viewed as a lapse in research ethics. Companies operating in this cutting-edge space might be tempted to keep things secret for IP reasons or to control public narrative, but doing so can undermine scientific integrity and public trust. Regulators and funding agencies encourage open science practices for medical breakthroughs. In the long run, Neuralink will need to engage fully with the scientific community – publishing data, allowing independent experts to vet claims, and following norms of reporting – to legitimize its technology for medical use. The **FDA approval process** itself enforces some rigor, as safety and efficacy must be demonstrated in documented trials. But beyond regulatory filings, the broader neuroscience field benefits from shared knowledge (for example, publishing how Neuralink addressed the thread migration issue could help others avoid similar pitfalls). There's an evolving conversation about balancing corporate secrecy with ethical responsibility when the "product" is an invasive device that affects human lives. The consensus among ethicists is that **accountability** is key: companies should be held to high standards of evidence and open communication when introducing devices into humans.

Equity and Access: If and when neural implants become viable treatments, questions of **who gets access** and who can afford them will arise. Cutting-edge therapies often start expensive. There's a risk that BMI technology could create disparities – benefiting wealthy patients or those in developed regions first, while others are left behind. Over time, costs usually come down with scale and insurance coverage, but it requires proactive effort to ensure these advances are equitably accessible. Moreover, if we consider hypothetical enhancement uses, there is a social justice concern that cognitive enhancements could be available only to some, potentially widening societal gaps. Policymakers and ethicists are already calling for frameworks to prevent BMI tech from exacerbating inequality. At the current stage, with devices only in trials, the focus is on safety rather than distribution. But we should keep in mind the ultimate goal: **sustainable, inclusive technology** that benefits a broad range of people who need it, not just a privileged few. This aligns with viewing BMI through a "sustainable futures" lens – it should contribute to well-being on a large scale, and

that means planning for affordability, training of clinicians to provide it, and public reimbursement if proven effective (so that a person with severe disability isn't denied a life-changing device due to cost).

Human Identity and Agency: A more philosophical consideration is how brain-machine integration affects our sense of self. When a device is reading your thoughts and potentially writing signals into your brain, the boundary between human and machine blurs. Users have reported that using a BCI can feel natural – in the best cases, the device becomes an extension of the mind, like an extra body part. But some worry about a loss of agency: if an algorithm is filtering or adding to your neural activity, are *you* fully in control? The Frontiers conceptual analysis noted the "bidirectional" nature of Neuralink-type devices raises uncertainties about enhancement of healthy individuals and extraction of information that invades privacy. If healthy people were to get BCIs to boost memory or multitasking, would that alter what it means to be human or create new social divides? While those scenarios are not immediate, the discussion of *neuroethics* urges us to tread carefully. Ensuring that any brain implant operates under the user's explicit control and consent is fundamental – e.g., devices could have **manual off-switches** that patients can activate if they ever feel uncomfortable or want a break from the interface. Furthermore, any cognitive enhancement use should be preceded by extensive ethical deliberation and probably regulation, given the societal implications (similar to how performance-enhancing drugs are controlled in sports, one might imagine cognitive enhancers being regulated).

Regulatory Landscape: Currently, neural implants are regulated as medical devices. In the US, the FDA's device approval process (including Investigational Device Exemptions for trials, and ultimately Pre-Market Approval for high-risk devices) is the gatekeeper for clinical use. The FDA will assess safety (e.g. risk of injury, infection, failures) and efficacy (does it meaningfully help patients) based on trial data. Neuralink's breakthrough designation for vision and the ongoing trials indicate the FDA is engaged. One challenge for regulators is that this tech spans multiple domains – it's a combination of implantable hardware, software/AI, and potentially cloud-connected systems. It also intersects with data regulations (like HIPAA for patient data security). There may be a need for **new guidelines specific to neurotechnology**, something ethicists and legal scholars have been advocating (including the idea of "neurorights" being enshrined in law, as some countries like Chile have started to do). Internationally, standards will need alignment, as neurotech companies operate globally. An interesting note: at least 42 people worldwide had received some form of BCI implant by 2023 in research contexts, indicating we are moving beyond isolated experiments into a larger domain that regulators must supervise consistently. It's likely that regulatory bodies will increase requirements for post-market surveillance (to monitor long-term effects on patients), cybersecurity standards, and perhaps certification of surgeons and hospitals that can perform these delicate implant procedures.

In summary, **ethical and regulatory considerations** form a crucial layer around neural implant technology. Addressing these proactively is as important as solving technical hurdles. Stakeholders – including companies like Neuralink, clinicians, ethicists, regulators, and patient representatives – must collaborate to establish frameworks that ensure the technology is developed **responsibly**. This means prioritizing patient safety and informed consent, ensuring transparency and peer oversight in research, protecting the privacy of neural data, preparing for equitable access, and guarding against potential abuses or unintended consequences (like coercive use or premature commercialization without proof of safety). The excitement around neural implants must be matched with a commitment to ethical diligence, so that public trust in these innovations can be maintained. As one ethicist noted, we should remember "the enormous upsides" of neurotechnology to alleviate suffering, while carefully managing the risks. When done responsibly, advancements in neural implants can proceed in a way that upholds human values and rights even as we integrate cutting-edge machines with our minds.

Future Directions and Conclusion

Neural implant technology for brain-machine communication is advancing rapidly, and the coming years promise both exciting developments and important ongoing challenges to overcome. Looking ahead, several **future directions** can be anticipated:

- **Expanded Clinical Trials and Indications:** In the near term, we will see the results of Neuralink's **PRIME Study** and similar trials from other companies. These early human studies will answer key questions about safety and what level of functional improvement can be reliably achieved (e.g., how fast and accurately can average users type with a BMI? Can multiple devices – such as a computer and a robotic arm – be controlled simultaneously?). Assuming safety benchmarks are met, trials will likely expand to include more participants, including those with different conditions. For instance, Neuralink or others may initiate studies for people with ALS (as already listed in Neuralink's trial criteria), spinal cord injury, stroke, or locked-in syndrome. Additionally, *feasibility trials for new indications* will progress – Neuralink's **CONVOY Study** aims to have BMI users control robotic prosthetic arms, moving beyond cursor control. The visual prosthesis (Blindsight) will also move into human testing, gauging how well artificial vision can be induced. Each new trial that demonstrates positive outcomes will build momentum and could lead to **regulatory approvals for clinical use** in specific scenarios (perhaps within a few years for a use like enabling text communication in paralysis, if results are strong). Regulatory agencies might grant humanitarian or limited approvals before full commercialization, to allow patients with urgent needs to benefit sooner under careful monitoring.

- **Technical Refinements:** On the technology front, we can expect **increases in channel counts and density** of implants. Neuralink's device with 1024 electrodes might be iterated to higher numbers (they already demonstrated 3072 in animalsjmir.org). Other groups are working on flexible electronics that could blanket larger brain areas with thousands of contact points. An important development would be achieving *greater coverage*: currently, one N1 implant covers a few millimeters of cortex with its threads. To interface with broader networks (say, both motor and sensory areas, or multiple limbs), a person might require multiple implants or a wider array. Neuralink's surgery robot and approach could theoretically allow multiple units to be installed, though surgical time and complexity increase. Future systems might use *modular implants* that snap together or communicate with each other to cover larger brain regions while still only having one point of wireless communication. **Wireless improvements** are likely as well – possibly higher bandwidth wireless links (maybe using ultra-wideband or optical telemetry) to transmit more data without draining battery, and better inductive charging methods for convenience (even exploring constant trickle-charge via a wearable, so the user doesn't have to consciously charge the device). Battery technology improvements could extend operation time and lifespan of the device (current implants might need battery replacement every few years, which would be another surgery unless rechargeable indefinitely). **Closed-loop capability** is another future refinement: integrating stimulation so that the device can not only read but also write to the brain in response to events. For example, a closed-loop BCI could detect an impending seizure and deliver a stimulus to abort it (combining BMI with a therapeutic function akin to a smart neuro-pacemaker). We will also see progress in **software**: more sophisticated decoding algorithms, perhaps using deep learning to decode more complex intentions (like imagining whole words or high-level goals rather than simple movements). Cloud-computing could offload heavy computation, though that raises latency and privacy issues – a balance will be sought between on-device processing vs. external processing. Companies might also leverage AI training on large datasets of neural activity (from trials) to pre-train decoders that generalize better, reducing calibration time for new users.

- **Improved Biocompatibility and Form Factor:** Materials science advances may yield electrodes that cause even less tissue reaction – for instance, using **bio-dissolvable support materials** that disappear after insertion, leaving only the tiny conductive traces embedded. Research is ongoing into electrodes made of carbon nanotubes or graphene, which are ultra-thin and flexible, or into **hydrogel coatings** that make electrodes "softer" once in the brain. Some teams are exploring **fully biological electrodes** (like engineered neurons that act as relays), though that's very experimental. The physical *size* of implants will also likely shrink. Neuralink's implant is already small, but an ultimate goal would be to have it entirely unobtrusive – potentially implanted through a small burr hole rather than a larger skull flap. Elon Musk has talked about aiming for a device so seamless that an incision and perhaps a laser-drilled skull hole are all that's needed, analogous to LASIK eye surgery's ease. We may see **minimally invasive delivery** for certain interfaces; for example, combining Neuralink's threads with endoscopic or catheter-based placement to avoid a full craniotomy. The synergy of different approaches might occur: maybe a device that partially goes through blood vessels and then exits into brain tissue in targeted spots (a hybrid of Synchron and Neuralink concepts). Also, there could be development of **removable interfaces** – perhaps something that sits on the dura and can be taken out if needed, to alleviate long-term implant concerns, though that typically sacrifices some signal quality.

- **Ethical Frameworks and Standards:** As the technology matures, we will likely see parallel development of **ethical guidelines, standards, and perhaps legislation** specific to neurotechnology. For instance, standards for neurodata encryption and patient consent could be issued by international bodies or national standards organizations. We may also see the emergence of **NeuroTech Ethics Boards** or inclusion of neuroethicists in trial review processes routinely, to ensure that as capabilities expand (especially towards any enhancement use-cases) there is proper oversight. If BCIs start moving beyond strictly medical indications, public discourse and legal regulation will intensify around questions like cognitive liberty and "neurorights." Some countries may move faster in adopting these technologies (for example, the US and EU are active, but also China has significant BCI research initiatives); this could lead to a need for global consensus on responsible use, perhaps via the WHO or similar institutions. On the regulatory side, if early devices prove their worth, authorities will craft guidelines for *market approval* and reimbursement. Over the next decade, we might witness the first **BMI device receiving full approval for clinical use**, maybe for a condition like severe paralysis to control computer/communication devices. That would set precedents for how such devices are evaluated and monitored (likely via patient registries to track outcomes and any adverse events long-term).

- **Integration with AI and External Systems:** Future brain-machine systems will likely integrate even more with AI-driven external software. For example, an AI could interpret a user's neural signals to not just execute a direct command, but to infer higher-level goals and assist proactively. If a user thinks "open my email" and then mentally composes a sentence, an AI agent could help auto-formulate the email once it interprets the intent. This merges BMI with the trend of AI assistants. Conversely, AI could provide sensory or analytical input to the brain via stimulation (imagine an AI detecting something important and signaling the user through a subtle neural cue). These kinds of integrations raise new scenarios – some very beneficial (streamlining the interface, adapting to the user), and some possibly concerning (could AI manipulate a user's mental state via their implant?). Research and ethical oversight will have to guide these possibilities carefully. Nonetheless, it's reasonable to foresee that BMI users will eventually harness AI to customize and optimize their device use, making the tech more powerful and user-friendly.

Conclusion

In conclusion, the field of neural implants enabling brain-machine communication is at an inflection point. Over the past two decades, foundational research demonstrated the *potential* of BCIs in isolated cases; now, companies like Neuralink are engineering that potential into integrated systems that could be deployed at scale, backed by robust data. This systematic review has examined how Neuralink's approach – with its high-bandwidth wireless implant – exemplifies the latest advancements in neural interface design, and how it compares to other cutting-edge solutions. We have seen that Neuralink's device **successfully allowed a paralyzed person to control digital devices at will**, a milestone that validates years of innovation. We have also recognized that many challenges remain, from ensuring long-term safety and stability of the implants in living brains to grappling with the ethical and societal implications of merging minds with machines.

From a broader perspective, these technologies align with the vision of a more **sustainable and inclusive future** – one where debilitating medical conditions can be ameliorated by technical means, thus improving quality of life and reducing the healthcare and economic burdens of disability. A paralyzed individual using a brain implant to work a computer or communicate effectively gains independence and can contribute more actively to society, which is a clear social good. Likewise, if blindness could be partially cured by a visual prosthesis, it would open opportunities and reduce reliance on assistance. These outcomes resonate with the goals of sustainable development in health and well-being. However, for such benefits to be realized on a broad scale, the technology must be made safe, affordable, and ethically deployed. This will require continued interdisciplinary effort – engineers, neuroscientists, clinicians, ethicists, and policymakers working hand in hand.

In the coming years, we anticipate not only engineering triumphs (more capable and user-friendly neural implants) but also the development of **comprehensive frameworks** that ensure these neurotechnologies are used to *enhance human welfare* without compromising ethical values. It is an endeavor very much in progress: as one commentary put it, *"we are living in exciting times"* with real hope that neural interfaces can "move paralyzed limbs, silence involuntary movements, and beyond". Caution and optimism must go together. With careful navigation of the challenges discussed, advancements in neural implants like Neuralink's will likely herald a new era of brain-machine symbiosis – one where people suffering from neurological limitations can reclaim abilities and perhaps even achieve feats previously unimaginable. The systematic pursuit of this vision, underpinned by rigorous science and ethics, will shape the frontier of sustainable, human-centric technology in the 21st century.

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Examining the Use of Artificial Intelligence in Space Technologies, Taking Into Account the Dimensions of International Law

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Abstract; With the remarkable developments in space technologies, artificial intelligence has gradually been used instead of humans in decision-making. Artificial intelligence has the ability to think logically, manage its own actions, and correct decisions in the event of changes in external conditions. New smart space technologies are being developed with the aim of performing various space activities such as processing space data and information, removing space debris, extracting natural space resources, and exploring without human intervention.

However, the regulation of the activities of space actors, especially private actors, and the supervision of these activities by states in the use of these types of technologies has become one of the new issues in the field of international space law.

Since the obligations of States within the framework of international space law are explained on the basis of human behavior, in the face of monitoring the performance of intelligent space technologies and compensation for damage resulting from their performance, the question arises as to whether the existing international space regulations on the international responsibility of States for monitoring space activities and compensation for damage, which are based on human behavior, can also be applied to the use of these technologies, or should the regulations be A new space law should be developed.

With a broad interpretation of Articles 6 and 7 of the 1967 Outer Space Treaty regarding the responsibility of States for monitoring space activities and also the responsibility for compensation for damage, these provisions can still be considered applicable.

Nevertheless, it seems that the development of new international space regulations could be an important step in better defining and recognizing the responsibility of states to monitor the use of intelligent space technologies by space actors and to compensate for damages resulting from them.

Keywords: International Law, Artificial Intelligence, Space Technology, Liability

Introduction

Artificial intelligence is a computer system that operates to some extent similar to the human mind and includes cognitive technology that imitates the human mind. To the extent that artificial intelligence can make decisions for humans, the role of the human agent becomes less important. Therefore, with the development of the use of artificial intelligence in new technologies, including space technologies, human intervention in decision-making has gradually decreased and artificial intelligence has gained the ability to make decisions instead of humans in various situations. (Abashidze et al., 2022:. 1)

Since the beginning of space activities, from the 1960s to the present, the use of space technologies such as spacecraft and satellites or the use of space robots in the extraction of natural resources Celestial missions have usually been carried out by astronauts who have human intelligence and behavior.

However, in recent years, there have been remarkable developments in space technologies, especially satellite systems and space-based services, which use artificial intelligence to make decisions instead of humans.

Since the nature of spacecraft provides a suitable platform for the development of artificial intelligence, and almost all space activities such as remote sensing and remote communications have the ability to use artificial intelligence, modern intelligent space technologies are currently being used for space debris removal, natural resource extraction in space, and exploration.

By using these technologies, better services in various fields, including transportation, smart city management, ensuring national and cybersecurity security, agricultural services, and monitoring climate change, are provided to the public.

Despite the benefits of using artificial intelligence in space technologies, with the expansion of intelligent space-based services, new challenges have emerged in the field of space activities. The use of technologies equipped with artificial intelligence for the purpose of exploring outer space, as well as participating in commercial space applications and services, will have unintended consequences regarding the obligations and responsibilities of States.

These consequences arise from the correct or incorrect use of such technologies and cannot be ignored. It is possible that due to inefficiency in the functioning of artificial intelligence, which makes decisions independently of humans, damage to life and property of people on Earth or in space could occur.

Also, the use of space-based applications equipped with artificial intelligence increases the possibility that the rights related to the privacy of individuals will be violated or the security of citizens will be jeopardized.

With the increase in the volume of data, spatial information and its processing through artificial intelligence, a lot of information is becoming widely available to the public. Among this information and data, confidential or private information of real and legal persons may also be disclosed without their consent.(Martin &.Freeland, 2020: 278)

Whereas the issue of State control over space activities and compensation for damage is clarified in international space law and the responsibility to prevent the commission of internationally wrongful acts under Article 6 and the responsibility to compensate for damage under Article 7 of the Convention on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, 1967 (the Outer Space Treaty) requires a connection between It has been proven that negligence and damage are caused by human behavior. The question arises whether the responsibility for monitoring the activities of space actors, including private actors, can be specified and determined based on these regulations, while human behavior is reduced or completely ineffective with artificial intelligence decision-making.

In this article, current international space law and the possibility of applying international regulations to the challenges posed by the use of artificial intelligence in determining the responsibility of States for surveillance and compensation for damages will be examined. By interpreting these articles broadly, with regard to the competent State, responsibilities for space activities in space technologies that use artificial intelligence can also be determined for States.

Also, clarifying the responsibility of Contracting States in the use of space technologies that use artificial intelligence in treaty law could be an important step in international law. Be spatial.

International Space Law Approach to the Use of Artificial Intelligence

In general, the development of artificial intelligence in space technologies currently faces a lack of binding international regulations and has not yet been explicitly and directly addressed within the framework of space "hard law" and "soft law."

Space "soft law," which has played a significant role in regulating space activities in recent years, has not provided regulations or guidelines for dealing with states regarding liability for the use of artificial intelligence in space technologies. Although in 2018, issues related to the use of artificial intelligence technologies in space were raised as part of the activities of the Committee on the Peaceful Uses of Outer Space (COPOS), and the topic of the work order this year was specifically the use of artificial intelligence for processing satellite images, the examination of this issue was removed from the work order of this committee without any concrete results or legal achievements. Since then, the topic of artificial intelligence has not been included as a separate and independent topic in the COPUS agenda. (Report of the Committee on the Peaceful Uses of Outer Space, 2018)

The "hard law" of space, which has so far been ratified by the United Nations in the framework of five international treaties, governs space activities. Of these five treaties, four are international space treaties – namely, the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Spheres, 1967 (Outer Space Treaty), the Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Abandoned in Outer Space, 1968, and the Convention on International Liability for Damage Caused by Space Objects, 1972 (Space Liability Convention). (1972) and the Convention on Registration of Objects Launched into Outer Space (1974) have been put into force, and the fifth treaty, the Agreement Governing the Activities of States on the Moon (and Other Celestial Bodies), (1978) has not yet been put into force, despite the passage of more than 45 years since its ratification (Mahulena, 2019, p. 32). (Masson-Zwaan & Mahulena, 2019: 32) These five treaties contain explicit provisions on the use of intelligent technologies. They are not artificial and only state general principles for all space activities.

In general, these general principles and rules mainly concern the following:

(1) The exploration and use of outer space shall be for the benefit of all States.

(2) Space shall not be subject to the national occupation and possession of any State and space activities shall be conducted in accordance with international law.

(3) Space activities shall be based on the principle of cooperation and the obligation to take into account The interests of other States in this regard shall be taken into account.

(4) States shall inform the general public and the scientific community of the nature, course, locations and results of their space activities.

(5) States shall be responsible for all national activities in the international arena and vis-à-vis other States and, in the event of damage, shall make reparation for the damage.

Among the principles mentioned, since the principle of responsibility enshrined in international space regulations and the There are no clear and transparent governments and regulations on AI issues in space technologies, especially in the area of liability, it can be argued that the starting point of the legal challenge should be the use of AI to adapt the rules and principles of liability to the performance of AI.

The use of AI systems in space activities will cause gradual changes from human analysis and selection with the help of computers and computer selection by humans to Information analysis and machine automation without the need for human performance, and decision-making and its implementation have been made independently by artificial intelligence. (Cuellar, 2017:. 30)

Challenges of International Space Responsibility

The deployment and use of artificially intelligent space objects by new space actors in space has raised the issue of how to assign international responsibility to contracting states; Because the principles of liability in these treaties on issues such as surveillance of space activities, compensation for damage to property and persons, and ultimately the disclosure of data and information of individuals and the violation of their privacy in space activities are based on human-centered behavior, and their application to behavior based on artificial intelligence requires new examination. (Stewart, 2019: 2)

To respond to this new challenge, it is necessary to first examine existing international space law. It should also be clarified whether existing international rules on liability are also applicable to the consequences of the use of artificial intelligence.

Liability for the supervision and regulation of space activities

The 1967 Outer Space Treaty of the United Nations recognizes States as internationally responsible for space activities. Article 6 of the Outer Space Treaty states that "States Parties to the Treaty have an international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried out by governmental agencies or non-governmental entities, and to ensure that national activities are carried out in accordance with the provisions set forth in the present Treaty."

Activities of non-governmental organizations in outer space, including the moon and other celestial bodies, shall require the authorization and continuous supervision of the appropriate State Party to the Treaty.

Whenever an international organization carries out activities in outer space, including the moon and other celestial bodies, the responsibility for compliance with this Treaty shall lie with that international organization and with the States Parties to the Treaty participating in that organization.

According to Article 6 of the Outer Space Treaty, it is the international responsibility of States to supervise space activities, whether these activities are carried out by a State or by a private entity under the jurisdiction of a State. Two essential elements, namely the issuance of the necessary permits and the supervision of space activities, play a fundamental role in attributing responsibility to States.

The activities of private companies in outer space will require authorization from and ongoing supervision by a Contracting State that has the necessary authority for this responsibility.

Indeed, States have been recognized as the main players in space activities, regardless of whether the space activities are scientific or commercial in nature and whether they are governmental or private. States that are parties to the treaty undertake to issue licenses for the space activities of their companies in accordance with national laws and to continuously monitor their performance. (von der Dunk, 2015:. 1)

On the one hand, it follows from Article 6 of the Outer Space Treaty that States are obliged to monitor the performance of their public and private sectors on the basis of the occurrence of internationally wrongful conduct and unlawful acts.

International law is violated by any Contracting State when space activities of its public or private entities are carried out without a valid license or when the Contracting State does not maintain continuous surveillance of space activities. On the other hand, it is inferred from the contrary meaning of this article that a State that properly and effectively implements a licensing and surveillance regime for its domestic entities is not held responsible.

Therefore, the non-realization of the responsibility of a Contracting State is proven when it is proven that, despite the necessary supervision of space activities by the State, the activities that have caused the damage were carried out by the private sector illegally and without authorization in the territory of that State or under the jurisdiction of a third State.

It is also inferred from Article 6 of the Outer Space Treaty that the doctrine of wrongful act allows a claim of liability against a State that has failed to fulfill its obligation to authorize and supervise space activities within its jurisdiction, even if no damage has been caused. Under this article, sufficient evidence is found for the international responsibility of a State that authorizes space activities under its jurisdiction without proper and reasonable supervision.

Therefore, the space law treaty regime does not impose any direct obligations on non-governmental entities. In return, it assigns all responsibilities and obligations to space actors, i.e., states, and states that the space activities of non-governmental organizations are subject to limited state oversight and that the treaty regime does not apply directly to the private sector.

Therefore, if space actors do not conduct space activities under the supervision of their own State and conduct space activities under the authority of a third State, the question arises as to which State – the State of those actors or the third State – bears the international responsibility of these private space actors (Cheng, 1995:307). In international space law, in the case of liability for compensation for damage or liability for the registration of a space object, the State The launcher is recognized as the responsible State in the 1972 Liability Convention and the 1974 Convention on Registration of Space Objects, respectively.

However, this term is not used in Article 6 of the Outer Space Treaty, which deals with the supervision of space activities. This article refers to the "appropriate State or competent State" and requires it to ensure that the space activities of its governmental and non-governmental entities are in accordance with the Outer Space Treaty.

Since neither this article nor any other article of the treaty regime on space law defines the term "competent State", there is no agreed legal standard for determining the "competent State". Of course, with a narrow interpretation based on the two Liability Conventions and the Registration Convention, the launching State can be considered the same as the competent State, while with a broad interpretation, the competent State can be extended to States that are more suitable for supervising their subordinate institutions, even though they are not the launching State. (Cheng, 1998:. 7)

The Contracting State shall also exercise its responsibility for the supervision of the intelligent space object under the standard of care. The Responsible State shall ensure that it has issued the necessary authorization for an intelligent space object launched by a non-State entity and has exercised appropriate supervision over its activities, whether or not it is owned or operated by one of its nationals. Therefore, by analyzing the standard of care for the occurrence of a specific event that caused the damage, the answer to the question of whether the competent government has issued the necessary permits for the activities carried out by the intelligent space object and has exercised sufficient supervision over it or not is different.

Here, if a state's public or private sector plays a role in the use of artificial intelligence in space technology and is not the launching state, this state can also be held liable based on a broad interpretation, even though

it is not the launching state. However, if only the launching State is held internationally responsible, new rules must be established in space law. (Dennerley, 2018: 281)

Therefore, compliance with the standard of care of the competent State requires ensuring that that State issues a permit and monitors space activities carried out using an intelligent space object. Compliance with this standard is an expression of the provision of a flexible standard in space law.

The obligation to "due care" is not an obligation to achieve a specific result. Rather, it is an obligation of conduct and of means that requires a contracting state to exercise sufficient and necessary diligence to prevent harm or injury to another state or its nationals. Violation of this duty is not limited to the actions of the state, but also includes the conduct of its own citizens (Messerschmidt, 2013:. 303).

However, based on flexible standards of oversight, it seems that the performance of the intelligent space object determines whether or not human intervention or oversight is needed and, if so, what is the appropriate degree and extent of such oversight.

The flexibility of the standard of supervision is in line with the approach generally recognised by the European Commission (EC) on AI. (European Commission, White Paper on Artificial Intelligence, COM, 2020)

The EU's position is that human supervision is a necessary component of the use of AI, arguing that human supervision ensures that "the AI system does not undermine human autonomy or create other adverse effects." "Human oversight" requires appropriate human(s) participation, which may vary depending on the "intended use of the AI system" and its impact on individuals and legal entities, "if any." The European Union has also identified some manifestations of human oversight in the use of AI, including:

(1) Reviewing and validating AI decisions before or immediately after the decision is made.

(2) Monitoring the AI system while it is operating and being able to intervene in real time and deactivate the AI system.

(3) Implementing operational constraints to ensure that certain decisions are not made by the AI system. Artificial.

According to the above, the European policy on providing a flexible framework for the specific issue of artificial intelligence in space technology could be a model for the future use of explicit international space law.

This approach determines whether the competent State's performance is consistent with its standards of oversight in the case of a non-State intelligent space object that has caused harm in outer space. The standard could, by hypothesis, be "due care" and supervision for the liability of the armed State for damage caused by an intelligent space object. This flexible standard allows the launching State, which is held liable in contractual cases, to argue that the State of origin of the non-State space actor has a greater role and responsibility than the launching State.

Accordingly, the launching State can deny liability on the grounds that the State whose citizens are using the space object The State Party that has an effective role should exercise due diligence in issuing adequate licenses and oversight.

This shifts the oversight obligation from the launching State to the home country of the non-State space actor. Failure by the space actor's State Party to properly implement due diligence standards in this regard may, depending on the circumstances, result in exemption or reduction of the liability of the launching State Party.

Liability for Compensation

According to Article 7 of the Outer Space Treaty, in the event of damage caused by space activities, the damage must be compensated by the responsible State to the injured State. Article 7 of the Treaty states that "any State Party to the Treaty which launches or causes to be launched an object into outer space, including the moon and other celestial bodies, and any State Party from whose territory or installations an object is launched, shall be liable for damage caused by the said object or its constituent parts on the earth, in the air or in outer space, including the moon and other celestial bodies, to any other State Party to the Treaty or to its actual or legal nationals." Internationally, it is responsible."

The basic rules in Article 7 of the Outer Space Treaty of 1967 regarding liability for damage are set out in detail in Articles 2 and 3 of the Convention on International Liability for Damage Caused by Space Objects of 1972. However, Article 7 of the said Treaty is very general and does not specify on what basis compensation should be awarded.

According to the appearance of Article 7 of the said treaty, it is inferred that the launching State has absolute responsibility. The above-mentioned Liability Convention has explained the subject of liability for compensation for damage in a comprehensive manner and has distinguished the basis of liability for damage caused in outer space from damage caused on the ground and in the air, and has made the criteria for liability the place of occurrence of the damage, i.e. the surface of the earth and the air above the earth on the one hand, and outer space, such as orbits or celestial bodies, on the other hand. (Lee, 2003:. 4)

Article 2 of the Liability Convention 1972 states that "the launching State shall be fully liable for damage caused by its space object to the surface of the earth or to aircraft in flight." Also, Article 3 of the Convention expressly states that "where damage is caused in a place other than the surface of the Earth to a space object of the launching State or to persons or property on board that space object by a space object of another launching State, the latter State shall be held liable if the damage is caused by the fault of that State or by the fault of persons for whom it is responsible."

According to the two articles above, liability is based on strict liability (or specific liability) for damage caused by a space object to property and life on the ground or to aircraft in flight, and liability based on fault is recognized for damage caused by a spacecraft in outer space or to a celestial body such as the moon.

Furthermore, the Convention emphasizes that the responsibility for compensation lies solely with States; Because non-state actors cannot be held accountable under international space law. With the development of space technologies and the use of artificial intelligence in them, the potential for activities in the dangerous environment of outer space has become even more complex, such that the attribution and enforcement of liability for damage resulting from the use of space technologies that use artificial intelligence is challenged under Articles 2 and 3 of the Liability Convention.

Attribution to artificial intelligence should replace attribution to the behavior of individuals who have played a role in the breach of obligation and liability, and the question will arise as to whether the provisions contained in the Outer Space Treaty and the Liability Convention can also be applied to the breach of obligations and damages caused by artificial intelligence

Absolute Liability

According to Article 2 of the Liability Convention, if a space object causes damage to persons or property on the surface of the earth or to aircraft in flight, absolute liability lies with the launching State.

By accepting the principle of absolute liability, which usually deprives the responsible individual of any right of defense, there is no difference between damage resulting from an artificial intelligence decision and

damage resulting from human behavior, and the launching state must compensate for the damage caused without resorting to the right of defense.

However, the Liability Convention still recognizes the right of the launching State to "effectively compensate for damage caused by the negligence, fault or recklessness of the injured party". According to Article 2 of the Liability Convention, launching States are fully liable for damage caused by their space objects on the surface of the Earth.

At the same time, in these circumstances, there is no obstacle to the legal prosecution of countries that use artificial intelligence technologies and are not the launching State. The complexity of the issue becomes apparent when such liability is to be established within the framework of Article 6 of the Liability Convention, which states the abolition of the strict rule of Article 2.

This article states that if "the launching State establishes that the damage was caused in whole or in part by gross negligence or by an act or omission of the claimant State or of natural or legal persons acting on its behalf with intent to cause damage, the claimant State cannot rely on the damage caused by the claimant State, since the claimant itself played a significant role in causing the damage."

It is practically impossible to exclude liability for damages caused by a space object equipped with artificial intelligence, because gross negligence is conduct that occurs by a human being, not a machine. The concept of "gross negligence" is not defined by the Convention and only refers to the "standard of care".

Some scientists conclude that "gross negligence" is, above all, a personal criterion and the result of the activity of the human mind, which in principle cannot be matched by the characteristics of a machine.

Therefore, in the absence of clear criteria for expressing the "standard of care" and taking into account the fact that it has been established depending on the level of scientific and technological progress, the implementation of the relevant provisions in the Convention on Liability for Space Technologies Using Artificial Intelligence is accompanied by great complexity, and it seems that new rules should be established in international space law..

Liability based on fault

Article 3 of the Convention establishes liability for various activities in outer space as being based on fault, but does not provide a definition of the concept of "fault". There are no clear criteria for assessing fault, and countries broaden or narrow this definition based on their own legal systems. It is relatively difficult to prove fault in the event of a collision between two spacecraft in outer space, and so far, no known case of damage in outer space due to a collision between spacecraft has been cited under the Liability Convention. (Long, 2014: 8)

Now, the extent to which the use of artificial intelligence has led to damage and injury in outer space must be added to the difficulty of using artificial intelligence in technology in the event of a collision between two spacecraft.

If the limits and scope of the interference of artificial intelligence are determined and its interference is less than the usual limit, the state that controls the spacecraft will be held liable under the Liability Convention. In other words, it is important to determine at what stage and to what extent artificial intelligence has been used in such technologies in the conduct of space operations.

Damages resulting from decisions made by AI or arising from data generated using AI technologies should be eligible. This depends on determining the extent of the direct and substantial impact of AI on space activities.

The term "persons" used in Article 3 of the Liability Convention also raises questions regarding the use of AI in space technologies. The term "person", as used in Article 3, usually refers to an entity, such as a natural or legal person, having legal rights, duties and obligations.

In interpreting Article 3 of the Convention, the responsibility for compensation for damage caused by a group or class of individuals must be assumed by the launching State. In a broader sense, this responsibility includes all individuals and all types of space activities.

Generally, we refer to an individual or person as a human being. In the context of law, the term "person/individual" generally refers to an identity and nature that is subject to legal rights and duties. Legal rules grant legal persons to companies and legal entities and subject them to duties and rights. In addition, in some specific cases, the law formally recognizes legal rights and obligations for some inanimate objects such as ships, lands and goods, and grants them rights and imposes duties on them that are subject to judicial jurisdiction and also to rulings against them.

However, in all cases of the aforementioned, the legal rights and duties imposed on artificial entities such as corporations or inanimate objects arise from acts or conduct performed by humans. The question now arises as to whether this basis should be extended to the issue of artificial intelligence (Solum, 1992: 1235).

The position of rights and obligations on persons is not necessarily true with regard to actions or behavior that are performed based on machine intelligence. A machine can learn independently of human information and behavior and make decisions based on the learning and information available, but this ability is necessarily accompanied by the acquisition of personality. Real or legal is not equal to him.

Decisions and behavior of individuals, both real and legal, are ultimately decisions made by humans; in this sense, decision-making is not based solely on reason or data, but is the product of various factors of human behavior such as consciousness, emotions, and choices. In the event that decisions and behaviors based on artificial intelligence are outside the scope of human supervision and management, without taking into account the factors Various human behaviors such as consciousness, emotions, and willpower, would be difficult to attribute to human behavior (Karnow, 1996: 190).

Therefore, since fault-based liability, under Article 3 of the Convention on the assumption of State fault, is based on the behavior of natural or legal persons, decision-making by an intelligent space object may not be attributable to "fault of individuals."

Accordingly, the assessment of liability The liability based on fault, under this Article, in respect of a decision taken by an intelligent space vehicle depends on whether such decision-making can be attributed to the launching State or the armed State. The liability based on fault of a Contracting State should not be based solely on the decision to launch the intelligent space object; since the acceptance of such a broad basis for liability is essential in the development and deployment of intelligent space objects and Their use in space will have an impact.

Therefore, the question of liability in these circumstances depends on the answer to the following question: When the damage is caused by an intelligent space object and human control is not involved in the occurrence of that damage, what conduct is necessary to attribute fault-based liability to a State (Kowert, 2017: 183)?

In view of the above, since Article 3 of the Convention does not establish liability for "fault of the State" or "fault of individuals", It is difficult to determine how a decision made by an intelligent space object can be considered at fault.

In the event of a collision between two spacecraft, it would be quite problematic to determine the liability of the launching State for damage caused by such an object acting completely independently. To solve this problem, it is necessary to consider innovative and complex issues concerning the standard of care, foreseeability of danger and damage, and proximate cause. Damages arise and the essential elements for establishing damages in liability cases should be analyzed with regard to the issue of artificial intelligence and it should be clarified how an intelligent space object can make decisions without the need for human action.

Responsibility for data protection and privacy

In general, one of the main concerns of space law in recent years has been the sharing of data and information of individuals in space technologies, which is likely to lead to a violation of the privacy of members of society. For example, data obtained through Earth observation can be analyzed using intelligent facial recognition technologies and combined with location data and data obtained from security cameras, and ultimately this information can be disclosed. Therefore, the issue of maintaining their confidentiality and preventing access to them without the necessary permissions, as well as, if these matters are ignored, compensation for damages, is seriously raised.(Soroka & Kurkova, 2019: 135)

In space management, the use of artificial intelligence puts the identity of individuals at greater risk. For example, very high-resolution imaging satellites are used to scan landscapes and streets, inspect them, record and capture images of buildings, cars, etc. for various purposes, including public advertising.

Users of these images may identify the observed areas or individuals in their vicinity. They are aware of and can recognize them and their movements, as well as their social patterns, and misuse this information. The real danger of placing this information in an unprotected location and the possibility of misuse of this information for any possible and unpredictable purpose and reason is

Active and advanced satellites can process data and information about people on the active satellite itself in orbit, without These satellites would need to be processed by humans at centers on the ground. In this case, only ground-related information would be transmitted, thus not only saving on communication costs with the ground and vice versa, but also allowing ground analysts to focus on the information that is most important.

Specialists could develop algorithms using artificial intelligence to analyze data, recognize images, and automatically correct and provide users with the ability to track individuals' assets and any kind of movement in any country. Therefore, with the use of artificial intelligence in data processing, the risk of misuse of data and spatial information increases.

Also, the use of artificial intelligence in space technologies by government agencies for extensive surveillance is of great importance for ensuring security. Thanks to satellite images, illegal cultivation of drugs in farms can be seen and Legal institutions can take legal action against violators based on evidence. However, these uses may violate laws related to the protection of personal data and information.

The use of these spatial data and information can violate human rights, especially in cases of discrimination and when there is arbitrary intervention by state and non-state institutions, and no trace of human activity can be found that can attribute these actions to him.

According to the above, the issue of The management and supervision of non-disclosure of information and the correct and lawful use of space data and information, and the exercise of State responsibility for the protection of individuals' privacy within the framework of State responsibility for monitoring space activities and compensation for damage, should be reviewed from an international perspective. On the one

hand, existing international regulations, in particular Articles 6 and 7 of the Outer Space Treaty, 1967, should be adapted to these conditions to determine whether they are applicable to these conditions or not. No, and, on the other hand, due to the importance of the issue, new specific regulations should be established for the use of data and information generated by space technologies equipped with artificial intelligence in order to eliminate legal gaps. (von der Dunk, 2013: 249)

First, to cover the liability of states against surveillance and damages caused by artificial intelligence decision-making regarding data and information generated by space technologies, the regulations contained in international space treaties should be

As stated above, Articles 6 and 7 of the Outer Space Treaty, without exception or condition, impose international liability on the launching State or the launching State. Therefore, in the event that the operation of intelligent space technologies is incompatible with the launching State or the registering State of the space object, international liability rules are applicable.

However, as stated in the previous section, these space treaties do not provide for liability based on fault. In the absence of human intervention, damages are not foreseeable and, in order to ensure liability for data surveillance and invasion of privacy, it may be necessary to pursue and consider other means of compensating for damage caused in space by an intelligent space object.

If a claimant State seeks compensation for damage or injury caused by an intelligent space object that falls within the meaning of "damage" as defined in Article 1(a) of the Liability Convention, 1972 It is not stated, such as damage resulting from the publication of data and the violation of the privacy of individuals, may be remedied by a broad interpretation of Article 7 of the Outer Space Treaty, because this article does not limit damages to material damages.

The 1972 Liability Convention expressly states that one of the main purposes of its codification is to establish rules and procedures relating to liability for damage caused by space objects, but the Convention does not claim that its rules and procedures should be excluded when assessing liabilities arising from means other than the Liability Convention.

Neither the Outer Space Treaty nor the Liability Convention precludes compensation for damage under Article 7 of the Outer Space Treaty. This is of great importance in view of the general principle of international law that "What is not prohibited is permitted."

In other words, in a particular case, it is not necessary to indicate the rules of permissibility as long as there is no prohibition. If, under Article 7 of the Outer Space Treaty, compensation for damage is not available under the Liability Convention, the interpretation of Article 7 of the Outer Space Treaty provides sufficient flexibility to address issues related to liability for the operation of intelligent space objects to address liability for the surveillance of their activities, as well as potential damages from disclosure of information and violation of the privacy of individuals. It will happen. (Tricot & Sander, 2010: 323)

Despite the broad interpretation of Article 7 of the Outer Space Treaty to protect individuals and their privacy, new international rules and regulations are needed; because clear and transparent rules can help resolve disputes between States regarding liability and compensation for damages.

Currently, there are no separate rules and regulations to address issues related to the use of artificial intelligence. In the processing of data and information, some legislators at the regional and national levels have developed guidelines that can be used as a model in space law to deal with artificial intelligence decision-making at the international level.

As mentioned earlier, one of the important and noteworthy documents is the General Data Protection Regulation in the European Union, which came into force in 2018 (Shaping Europe's digital future, "A European Strategy for data").

European Strategy for the Use of Artificial Intelligence in In addition to providing information to create an agile, secure and dynamic economy in the world and to improve decision-making and provide a better life for all citizens, technologies are set to define a supervisory framework for the future by creating a "trust/assurance ecosystem". To do this, it is necessary to ensure compliance with EU law, including the laws protecting fundamental rights and consumer rights, in particular regarding systems Artificial intelligence has been described as high-risk. Therefore, EU regulations focus on building trust between consumers and various stakeholders in the field of artificial intelligence and informing them about the risks of artificial intelligence (European Commission, White Paper on Artificial Intelligence, COM, 2020). The United States is also among the technologically advanced countries that are trying to formalize legal measures against AI-related events and regulate such measures. Compile. Generally, legal actions for damages caused by a device or machine are recognized as a form of negligence on the part of the owner or user, and are based on the theory of producer liability, which requires human intervention to be established.

It seems logical to hold the producer liable for defects in design or construction of software and failure to warn of foreseeable harm. Design Defects A product or technology is defective when there is a risk of foreseeable harm and the designer could have avoided that risk or reduced the likelihood of that risk by using a reasonable alternative design. A defective manufacturing design occurs when a product is not manufactured to specifications and standards. Accordingly, negligence also occurs when the responsible party fails to properly follow "instructions for the safe use of software." (Giuffrida, 2019: 440)

Conclusion

The use of artificial intelligence in space technologies in enhancing its applications is undeniable. The development of artificial intelligence technologies creates unprecedented opportunities for space exploration and the implementation of new types of space activities.

However, space objects launched into space by governments and private players are becoming increasingly technologically sophisticated and increasingly equipped with artificial intelligence technologies that enable space technologies to operate without human intervention. Such devices are used in particular to monitor the performance of satellites, act as assistants to astronauts, and conduct research when conditions are dangerous to humans.

The use of space technologies equipped with artificial intelligence will be accompanied by unintended consequences that arise from the use or misuse of such tools. Just as the use of artificial intelligence can be very useful and beneficial for the provision of social services, the use of this technology for the wrong purposes or by the wrong people can also cause significant damage to governments and people.

Space law should seek to address issues of oversight of the performance of artificial intelligence in space technologies, as well as liability for harm caused. Harm can be both material, such as endangering the safety and health of individuals, loss of life, damage to property, and non-material, such as violation of privacy, restrictions on the right to freedom of expression, human dignity, or discriminatory actions in various matters.

In addition to the responsibility for monitoring activities and liability for damages, space law should also address the monitoring of data and information storage, as well as the protection of individuals' privacy; in particular, the lack of a specific monitoring framework for non-state space actors, who often do not pay attention to individuals' privacy, could seriously harm the regulation of space activities in the future.

The mandatory space treaties do not explicitly address the use of AI, and no other international space regulation addresses the use of AI in space. The lack of international regulation on AI creates complex and potential problems regarding the applicable law in resolving disputes between States over liability for the use of AI in space technologies. If the use of artificial intelligence in space activities or a space object causes damage to another space object that is identifiable under the Convention on International Liability for Damage Caused by Space Objects, it is unclear whether the substantive rules and regulations that are used to determine issues related to the resolution of the level and quality of the claim, such as the standard of care and what constitutes fault-based liability, would be applicable.

According to a broad interpretation of Article 6 of the Outer Space Treaty, the responsibility of States in international space law is considered within the framework of surveillance based on the standard of "surveillance and oversight." A Contracting State must also exercise its responsibility for surveillance over a space object that uses artificial intelligence, according to the standard of surveillance.

The responsible State has a duty to ensure that the necessary authorization is issued for the launch of an intelligent space object by a non-state entity and to supervise it; if a State's space actor plays a role in the use of artificial intelligence in space technology, this State can be held liable based on a broad interpretation.

Compliance with the standard of due diligence requires that the competent State ensure that the necessary authorization is issued for space activities carried out using an intelligent space object and that that State supervises those activities.

The subject of compliance with this standard is the provision of a flexible standard in space law. The obligation to "due diligence" is a behavioral obligation that a Contracting State must take supervisory measures to prevent harm to another State or its nationals.

Also, in order to determine the liability of States for compensation for damage, with a broad interpretation of Article 7 of the Outer Space Treaty, in addition to establishing the absolute liability of States for damage to property and persons on the ground and on aircraft caused by their intelligent space technologies, States can be held liable for the conduct and performance of natural and legal persons based on the fault of which their intelligent space technology has caused damage in outer space. The determination of liability for damage caused by an intelligent space object in outer space is related to the ability to attribute fault-based liability to a State.

As mentioned, in addition to the possibility of a broad interpretation of Articles 6 and 7 of the Outer Space Treaty of 1967, it is possible to model the national space laws of some countries and encourage other countries to adopt this type of laws. European policy-making on the specific issue of artificial intelligence in space technology could be a model for the explicit use of international space law in the future.

This approach aligns the armed state's performance with its standards of care in the event of an intelligent space object causing damage in outer space. Arguably, a "due care" and oversight standard could be adopted for the armed state's liability for damage caused by an intelligent space object. This flexible standard allows the state of the primary space actor to be held liable.

Since these regulations lack the clarity and transparency necessary to address the issue of artificial intelligence, and Contracting States do not play an effective role in decision-making on artificial intelligence in space technologies, given the growth of private sector space players, it is desirable for the international space community of States to develop specific regulations within the framework of soft space law, i.e., guidelines and resolutions, and to encourage Contracting States to follow their example. Develop and implement national space regulations related to the oversight of space actors that use artificial intelligence in their space technology, and then, after establishing a specific procedure in the national space

laws of countries, international space institutions, such as COPUS, develop international regulations to establish the responsibility of the state responsible for overseeing the performance of the space actor.

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Mathematical and Statistical Methods in the Application Fields of Data Mining Technology

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Abstract; In today's digital age, enormous volumes of data are generated every moment. Data mining leverages mathematical and statistical methods—alongside machine learning, database management, and data visualization—to extract valuable knowledge from these large data sets. Its techniques are applied successfully in diverse areas, including business, government, healthcare, science, and sports, with use cases such as database marketing, fraud detection, retail analytics, credit scoring, astronomy, and molecular biology. Mathematics provides the backbone of these processes through statistics, optimization, linear algebra, probability theory, and other fields. Together, mathematical and statistical methods enable efficient preprocessing, accurate modeling, reliable forecasting, and optimization. Their integration makes large-scale data easier to process and analyze, ultimately supporting informed decision-making across multiple domains.

Application Areas of Data Mining

Data mining is applied across a wide range of industries. Its methods have achieved significant success in **healthcare, finance, retail, telecommunications, and marketing**. In fact, data mining technology can be implemented in all areas of human activity where retrospective data (researchers' reliance on past records or previously collected information) exists (Савченко & Бежитский, 2015). The main fields include:

- **Business problem-solving:** banking, finance, insurance, manufacturing, telecommunications, e-commerce, marketing, stock markets, and more.

- **Public sector:** detecting tax evasion, developing counter-terrorism tools, and other state-level applications.

- **Scientific research:** medicine, biology, molecular genetics and genetic engineering, bioinformatics, astronomy, and other sciences.

- **Web applications:** information-retrieval systems, web analytics, and traffic counters.

Through mathematics, data mining enables the analysis of information, the construction of models, and the discovery of hidden patterns. There is a close relationship between mathematics and data mining, as the field frequently combines **statistics, geometry, algebra, optimization, and probability theory**. Several core examples illustrate how mathematics is applied in data mining (Гаврилова & Хорошевский, 2001).

The Role of Mathematics in Data Mining

Mathematics is a widely used tool in **data mining**, applied across a variety of tasks ranging from data analysis to forecasting and optimization. Mathematical models and methods help data mining achieve more efficient and accurate outcomes. Their application facilitates the processing and analysis of large-scale data and provides essential information for making sound decisions.

In many cases, specialists need to understand the basics of mathematics to apply methods correctly. For other purposes, ready-made APIs or algorithms may be sufficient, but deeper insights require mathematical knowledge.

The **first stage of data mining** is **data preparation (preprocessing)**. At this stage, mathematical and statistical techniques are used to detect inexact, missing, or erroneous data. For example, faulty data can be identified and corrected through statistical or algebraic methods. Different mathematical approaches are applied to transform raw inputs into a usable format. In fact, data analysis and statistical modeling form the very foundation of data science, covering a wide spectrum of mathematical techniques and methods.

Core Methods Used in Data Mining

1. Mathematical methods:

- Linear algebra (vectors, matrices)
- Optimization methods
- Graph theory
- Discrete mathematics

2. Statistical methods:

- Regression analysis (linear and nonlinear)
- Correlation and covariance
- Hypothesis testing
- Probability distributions

Main functions of data mining include:

- **Classification:** assigning objects to defined categories.
- **Clustering:** grouping similar objects together.
- **Association rules:** uncovering hidden relationships among data.
- **Prediction/forecasting:** estimating future outcomes.
- **Anomaly detection:** identifying unusual or rare events.

Key Mathematical Foundations

Probability theory and statistics form the core of data analysis. Probability theory is essential for reasoning under uncertainty, such as in Bayes' theorem, which provides a framework for updating probabilities as new evidence becomes available.

Mathematical statistics covers the systematization, processing, and interpretation of data, and provides both scientific and practical conclusions. Here, "statistical data" refers to a comprehensive set of indicators describing an object. The foundation of mathematical statistics rests upon probability theory.

Meanwhile, statistics as a discipline is concerned with the collection, organization, analysis, interpretation, and presentation of data. This dual role—probability as the theoretical backbone and statistics as the applied practice—makes them indispensable for effective data mining.

Core Mathematical and Statistical Methods in Data Mining

Descriptive Statistics

Descriptive statistics include measures such as the mean, median, mode, standard deviation, variance, and range. These tools are used to summarize and understand data at a glance, providing a snapshot of key trends and variability.

Inferential Statistics

Inferential statistics involve drawing conclusions about a population from a sample. This is typically based on random sampling techniques. Common methods include hypothesis testing, chi-square tests, t-tests, and analysis of variance (ANOVA). These techniques allow researchers to generalize findings from limited data to larger populations with a defined level of confidence.

Linear Algebra

Linear algebra is the branch of mathematics dealing with vector spaces and linear mappings between them. It is a fundamental area widely applied in data analysis. Linear algebra focuses on matrices and vectors, solving linear equations, and studying linear functions. In simple terms, it helps to understand multidimensional geometric concepts and to perform calculations on them. Concepts from linear algebra are used in regression analysis, principal component analysis (PCA) for dimensionality reduction, and as the computational backbone of many machine learning (ML) models (Kharkovyna, 2019).

Calculus

Calculus, the study of continuous change, is applied in optimization tasks within data analysis and especially in machine learning. For instance, gradient descent is an optimization algorithm that iteratively moves in the direction of the steepest decrease in order to minimize a function. This relies on derivatives to determine the slope and direction of change, thereby helping to locate minima or maxima of loss functions.

Optimization Methods

Optimization techniques aim to find the best (or optimal) solution when constraints exist. Optimization problems arise naturally in data analysis and ML. For example, training a model often involves optimizing a loss function to improve predictive performance.

Graph Theory

Graph theory, a branch of discrete mathematics, studies the properties of graphs (nodes and edges). It is particularly useful in analyzing social networks, ranking web pages, and understanding relationships within large datasets. In data mining, graph-based methods help with network analysis and certain clustering algorithms.

Differential Equations

Differential equations describe the relationship between a function and its derivatives. Because such relationships are common across disciplines, differential equations play a central role in engineering, physics, economics, and biology. In data mining, they are used in **time-series analysis**, where data are modeled as functions of time. They also underpin processes such as **training neural networks**, where iterative updates can be represented as differential systems.

Matrix Operations and Decomposition

Matrix operations (multiplication, transposition, inversion) and decomposition techniques (e.g., Singular Value Decomposition, SVD) are fundamental in many data-analysis contexts. Machine learning projects often deal with complex objects such as audio, video, and images, where classifiers rely on linear algebraic techniques to extract features and reduce errors. Matrix decomposition serves as the computational engine behind the efficient processing of large, high-dimensional data sets. These methods provide the principles and tools necessary for converting raw data into useful, actionable knowledge.

Databases and Machine Learning in Data Mining

Data mining relies on two fundamental components: databases and machine learning (Brownlee, 2019a). The database component provides methods for storing, managing, and retrieving data, while the machine-learning component supplies methods for analyzing and interpreting that data.

It is important to note that data mining by itself does not "learn" independently. It follows predefined rules and algorithms to solve specific problems. In contrast, machine-learning algorithms can adapt, change their rules based on circumstances, and discover new solutions in flexible ways.

Types of Machine Learning

In the context of data mining, three main types of machine learning are commonly applied (Brownlee, 2019a):

- **Supervised learning.** In this approach, the algorithm is trained on input–output pairs that have been pre-labeled by humans. The system is provided with examples of the desired outcome, enabling it to map inputs to outputs and generalize to new data (Brownlee, 2019b).

- **Unsupervised learning.** Here, the input data are unlabeled. The algorithm searches for commonalities, patterns, and features within the data without predefined categories. Because unlabeled data are far more abundant than labeled data, this method is especially valuable (Mishra, 2017).

- **Reinforcement learning.** In this setting, the system learns by interacting with its environment, receiving rewards or penalties based on its actions, and gradually improving its performance.

Linear Algebra in Machine Learning

Linear algebra is one of the core mathematical tools in machine learning. Nearly all ML models are built on operations involving vectors and matrices. These concepts form the computational language of algorithms, making it possible to represent, manipulate, and optimize large and complex datasets.

The next section explores practical applications of linear algebra in ML, including data representation, linear models, neural networks, dimensionality reduction, similarity measures, and optimization.

Linear Algebra Applications in Machine Learning

1. **Data Representation**

   Observations (*samples*) and their properties (*features*) are often represented as **vectors** or **matrices**.
   Example: Exam scores of three students across three subjects:

$$x = \begin{bmatrix} 85 & 90 & 78 \\ 70 & 65 & 80 \\ 95 & 88 & 92 \end{bmatrix}$$

Here, each **row** corresponds to a sample (a student), and each **column** corresponds to a feature (a subject).

2. **Linear Models**

   Linear regression can be expressed as:
$$y = X\omega + b$$

   where X is the data matrix, ω is the weight vector, b is the bias term, and y is the output. Predictions are calculated simply through the product of a matrix and a vector.

3. **Neural Networks**

   In each neural-network layer, the output is computed as:
$$z = Wx + b$$

   where W is the weight matrix, x the input vector, and b the bias. These are linear algebra operations, followed by a nonlinear activation function.

4. **Dimensionality Reduction**

   o **Principal Component Analysis (PCA):** identifies eigenvalues and eigenvectors to reduce dimensionality while retaining maximum variance.

   o **Singular Value Decomposition (SVD):** projects data onto its most significant directions.

5. **Similarity and Distances**

   Linear algebra enables computation of distances and similarities:

   o **Euclidean distance:**

$$d(A, B) = \sqrt{\sum (a_i - b_i)^2}$$

   o **Cosine similarity:**

$$\cos(\theta) = \frac{A \cdot B}{\|A\| \, \|B\|}$$

These are widely applied in **natural language processing (NLP)** and **recommender systems**.

6. **Optimization (Gradient Descent)**

Training machine-learning models involves minimizing a loss function. Gradients, often represented as vectors or Jacobian matrices, are computed and used to iteratively update weights toward an optimal solution.

Conclusion

Linear algebra is the "language" of machine learning. Vectors, matrices, eigenvalues, orthogonality, and norms all stand at the foundation of ML. As a field, linear algebra—concerned with vectors, matrices, and linear transformations—is used not only in physics and engineering but also in computer science. Its applications in machine-learning algorithms include data analysis, prediction, classification, visualization, and regression (Mishra, 2017).

Thus, data mining combines mathematical methods and statistical analysis to evaluate and interpret information. These tools allow practitioners to understand customer behavior, make forecasts, discover relationships, and detect anomalies. From preprocessing to modeling and optimization, mathematics—particularly linear algebra—helps data mining achieve more accurate, efficient, and scalable results for decision-making.

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Impact of Theatre and Cinema Culture on Economy

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Abstract; Theatre and cinema have traditionally been regarded as cultural and artistic pursuits; however, their economic significance has gained increasing recognition in recent decades. This study explores the multifaceted economic contributions of these sectors, focusing on their roles in revenue generation, employment, tourism, and urban development. Employing a mixed-methods approach, the research integrates quantitative data from global and national economic databases with qualitative analysis from policy documents and industry reports. Results show that theatre and cinema industries contribute substantially to national GDPs, support millions of jobs worldwide, and stimulate economic activity across adjacent sectors such as hospitality, retail, and technology. The analysis also highlights the growing impact of digital transformation and streaming platforms, particularly in the wake of the COVID-19 pandemic. In addition, cultural tourism driven by theatrical landmarks and filming locations has proven to be a significant source of regional income. The findings underscore the need for governments and policymakers to treat these industries not merely as entertainment, but as strategic economic assets. This paper concludes with recommendations for public investment, policy development, and international cooperation aimed at sustaining and expanding the economic impact of theatre and cinema in both developed and developing economies.

Keywords: theatre, cinema, impact, economy, cultural hubs, cultural mirror, film industry

1. INTRODUCTION

The creative economy has emerged as a powerful engine of growth, innovation, and cultural diplomacy in the 21st century. Among the various components of the creative industries, theatre and cinema hold a prominent place, not only for their artistic significance but also for their substantial economic footprint. These art forms serve as cultural mirrors—shaping and reflecting societal values—while simultaneously contributing to economic vitality through job creation, international trade, and tourism.

Historically, theatre has been a cornerstone of urban life, dating back to ancient Greek and Roman civilizations where performances played vital roles in civic and religious life. With the rise of modern cities, theatres became cultural hubs, drawing local and international audiences. The economic role of theatre expanded during the industrial era as increased urbanization and disposable incomes fostered public demand for entertainment. In the 20th century, cinema emerged as a mass medium, transforming from silent black-and-white films to a global multimedia industry.

Today, both sectors are integral to the cultural economy, generating billions of dollars annually across production, distribution, and exhibition chains.

Globally, countries have recognized the importance of cultural industries in promoting soft power, attracting investment, and enhancing social cohesion. Blockbuster films and iconic theatre productions not only generate direct revenue through ticket sales but also stimulate indirect economic activity in adjacent sectors such as advertising, merchandising, hospitality, transportation, and digital platforms. Furthermore, film festivals, theatrical premieres, and major cultural events serve as magnets for cultural tourism, drawing millions of visitors and boosting local economies (Mammadova & Abdullayev, 2025).

In recent years, the landscape of these industries has been altered by technological advancements (e.g., streaming platforms, digital ticketing, virtual production) and global disruptions such as the COVID-19 pandemic, which temporarily shut down live performances and cinemas worldwide. Despite these challenges, the resilience and adaptability of the sector have underscored its economic and social importance. Theatres have begun integrating hybrid models of live and virtual performances, while cinema continues to evolve through international co-productions and cross-platform storytelling (Gulkhara & Farzaliyeva, 2025).

Despite this dynamic evolution, the economic impact of theatre and cinema is often underappreciated or overlooked in national policy frameworks. Many governments still view them primarily as cultural or leisure sectors rather than as robust contributors to gross domestic product (GDP), employment, and innovation. This underrepresentation hinders effective policy-making and investment strategies that could otherwise enhance their economic potential (Elza & Asif, 2025).

This paper seeks to address this gap by analyzing the economic dimensions of theatre and cinema. By examining indicators such as GDP contribution, employment statistics, box office performance, and cultural tourism data, the study aims to provide a comprehensive overview of how these cultural forms drive economic development (Farzaliyeva & Abdullayev, 2025). The findings will inform stakeholders—including policymakers, investors, and cultural institutions—on how to better leverage these sectors for sustainable economic growth and societal benefit (Mammadova & Abdullayev, 2025).

2. METHODS

This study employs a mixed-methods approach, combining quantitative data analysis with qualitative content review, to assess the economic impact of theatre and cinema. This approach enables a holistic understanding of both the measurable and contextual contributions of these cultural sectors to national and global economies.

2.1 Data Collection

Quantitative Data Sources

To capture the financial and employment contributions of theatre and cinema, secondary data were sourced from reputable international and national databases, including:

- UNESCO Institute for Statistics – for global cultural statistics, including employment in the creative industries.

- The Motion Picture Association (MPA) – for data on global box office revenue, employment in the film and television sectors, and economic impact reports.

- National Endowment for the Arts (NEA) – for U.S.-specific data on performing arts contributions to GDP and employment trends.

- Office for National Statistics (UK) – for data on the UK's creative economy, including theatre and film sub-sectors.

- Statista – for supplemental global data on box office trends, streaming revenue, and audience numbers across countries.

These data sources provided information from 2015–2023 to ensure that both pre- and post-pandemic trends were captured.

Qualitative Sources

For the qualitative component, peer-reviewed journal articles, industry reports, and policy documents were analyzed to explore:

- The broader socio-economic role of theatre and cinema

- Case studies (e.g., Broadway in New York, Bollywood in India, West End in London)

- Cultural tourism impacts

- Industry challenges and recovery post-COVID-19

Key databases consulted included Google Scholar, JSTOR, and Scopus, focusing on literature published between 2010 and 2023.

2.2 Data Analysis

Economic Indicators Assessed

The analysis focused on the following indicators to measure economic impact:

- Gross Value Added (GVA) and Gross Domestic Product (GDP) contribution of theatre and cinema

- Employment statistics (full-time and part-time)

- Box office revenue, ticket sales, and streaming platform income

- Ancillary revenues: merchandising, licensing, venue rentals

- Cultural tourism metrics: tourist visitation linked to theatre districts, filming locations, and festivals

Where possible, data were standardized in terms of national currency and adjusted for inflation using World Bank economic indicators.

Comparative and Longitudinal Analysis

Data were compared across key cultural economies (e.g., United States, United Kingdom, India, South Korea, and Nigeria) to highlight differences in industry scale and policy support. A longitudinal analysis from 2015 to 2023 allowed for assessment of industry growth trajectories and the impact of COVID-19 disruptions.

Triangulation

Quantitative data were triangulated with qualitative insights from industry experts, reports, and case studies to ensure validity and reliability of findings. For example, reports from the Broadway League and UK Theatre were used to interpret how revenue flows extend to surrounding sectors such as hospitality and retail.

3. RESULTS

The analysis of theatre and cinema reveals a strong and multi-dimensional economic impact across different regions. The results are grouped into four key areas: contribution to GDP, employment generation, revenue from box office and digital platforms, and tourism and regional development.

3.1 Contribution to GDP

Both theatre and cinema sectors contribute significantly to national GDPs through direct production and associated industries (Ahmedova, 2025).

- According to the National Endowment for the Arts (2022), the arts and culture sector (including theatre and film) contributed $1.0 trillion to the U.S. economy in 2021, accounting for 4.4% of GDP. The film and video industry alone contributed over $99 billion.

- In the United Kingdom, the Department for Digital, Culture, Media & Sport reported that the creative industries contributed £109 billion to the UK economy in 2021, with film, TV, and performing arts being among the highest-grossing sub-sectors.

- In India, the film industry (primarily Bollywood) contributed approximately ₹183 billion (US$2.5 billion) to the economy in 2022, rebounding post-COVID (FICCI-EY, 2023).

These figures reflect only the core contributions; the real economic footprint is larger when including indirect and induced effects on hospitality, retail, and transport.

3.2 Employment Generation

Theatre and cinema are labor-intensive industries, employing individuals across creative, technical, and administrative roles.

- The Motion Picture Association (2023) reports that the global film and television industry supports over 2.5 million jobs in the United States alone, across 122,000+ businesses, 87% of which are small enterprises.

- In the UK, the performing arts sector employed over 314,000 people in 2021, with 60% being freelancers.

- In Nigeria, the Nollywood film industry employs more than 1 million people, making it the second-largest employer after agriculture.

The employment impact also extends to indirect jobs in set construction, costume design, catering, marketing, and logistics (Sadikhova, 2025).

3.3 Box Office and Digital Revenue

Theatre and cinema generate billions in revenue through box office sales and increasingly through digital platforms.

- In 2023, the global box office generated $33.9 billion, a significant rebound from the pandemic low of $12 billion in 2020 (Statista, 2024).

- The Broadway theatre industry alone generated $1.58 billion in ticket sales in the 2022–2023 season, despite only partial recovery to pre-pandemic levels.

- The global streaming video market, driven by platforms like Netflix, Disney+, and Amazon Prime, was valued at $95 billion in 2022, with an expected CAGR of 12% through 2027.

- In South Korea, local film production revenue reached ₩1.2 trillion ($900 million USD) in 2022, with the country becoming a global cultural exporter thanks to films like *Parasite* and the rise of K-cinema.

These figures reflect the diversification of revenue streams in the post-pandemic world, with hybrid distribution models becoming increasingly profitable.

3.4 Tourism and Regional Economic Development

Theatre and cinema serve as catalysts for tourism and urban development.

- Broadway tourism in New York attracts approximately 14.8 million people annually, contributing over $14 billion to the city's economy in 2022 through ticket sales, hotels, restaurants, and shopping.

- In the UK, 23% of West End theatre audiences in 2019 were international tourists (Society of London Theatre, 2020).

- Film-induced tourism has become a recognized phenomenon, with destinations like New Zealand (due to *The Lord of the Rings*), Croatia (*Game of Thrones*), and Scotland (*Harry Potter*) experiencing substantial increases in tourism revenue. For example, *The Lord of the Rings* trilogy is credited with boosting New Zealand's tourism by 6% annually for a decade.

The spatial clustering of theatres, cinemas, and related businesses in districts (e.g., Hollywood, West End, Broadway) also contributes to urban regeneration and cultural branding.

3.5 Post-COVID Recovery and Sector Resilience

Theatre and cinema industries were among the hardest hit by COVID-19 due to closures and audience restrictions. However, recovery trends are promising:

- Live theatre ticket sales in major cities have rebounded to 80–90% of pre-pandemic levels by late 2023 (UK Theatre, 2023).

- Cinema audiences are gradually returning, but streaming remains dominant, especially for independent and international films.

- Governments in countries like South Korea, Germany, and Canada have introduced creative sector stimulus packages, recognizing the industries' economic and cultural value.

4. DISCUSSION

The findings underscore that theatre and cinema are not just cultural assets, but economic engines with multi-layered impacts (Ahmedova, 2023). Their contribution to GDP, employment, and tourism is both direct and indirect, spanning a wide network of sectors including hospitality, technology, education, and retail. However, the full economic potential of these industries is still undervalued in mainstream economic planning and policy discourse, especially in developing nations.

4.1 Strategic Economic Importance

Theatre and cinema serve as catalysts for both urban development and rural revitalization. In global cities such as New York, London, and Seoul, creative districts act as cultural and economic hubs. The presence of theatres and cinemas drives property value increases, promotes small business growth, and enhances the city's international brand identity. In rural or underdeveloped regions, investment in cultural infrastructure—such as community theatres or film festivals—can stimulate local economies, generate employment, and attract tourism.

Moreover, these industries act as value multipliers: revenue generated from a film or theatre production circulates through the economy, benefiting sectors such as logistics, construction, legal services, and fashion. This aligns with Porter's Cluster Theory (Porter, 1990), which posits that industries concentrated in a region create positive spillovers, innovation, and competitiveness.

4.2 Employment and Inclusion

The results confirm that the creative industries—especially theatre and cinema—generate high levels of employment, much of which is freelance or project-based. This flexibility is both a strength and a vulnerability. On one hand, it allows for agile production and innovation. On the other, it creates economic insecurity for workers, as shown during the COVID-19 pandemic when live events were suspended, and many artists lost income overnight.

Furthermore, the employment structure in these industries offers opportunities for diverse and marginalized groups, including women, LGBTQ+ individuals, and ethnic minorities, who often find limited opportunities in traditional sectors. However, persistent challenges regarding representation, wage equity, and job security remain. Addressing these issues requires deliberate policy interventions such as union protections, wage standardization, and diversity quotas in public funding.

4.3 Digital Transformation and New Revenue Models

The pandemic accelerated the digital transformation of theatre and cinema. While cinema faced declining ticket sales due to the rise of streaming platforms, it also opened up new revenue streams through video-on-demand (VOD), international co-productions, and subscription-based models. The theatre industry, traditionally reliant on in-person performances, began experimenting with livestreamed productions, hybrid performances, and digital ticketing.

This digital shift has created global audiences, where a Broadway production or an independent Korean film can reach viewers across continents instantly. For emerging markets, this represents an opportunity to export cultural content, build soft power, and earn foreign revenue. However, digital expansion also raises concerns about monopolization by large streaming platforms, the loss of local cinema ecosystems, and digital rights management—issues that require regulatory oversight.

4.4 Resilience and Recovery Post-COVID-19

The theatre and cinema industries showed remarkable **resilience** following the COVID-19 pandemic. Although severely affected in 2020–2021, recovery began in 2022 and accelerated in 2023. Government stimulus packages, such as the UK's Culture Recovery Fund (£1.57 billion) and Canada's COVID-19 Emergency Support Fund for Cultural Workers, played a key role in preventing permanent closures of theatres and production companies (DCMS, 2021).

Yet, recovery has been uneven across regions. High-income countries with strong public funding mechanisms rebounded faster, while low- and middle-income countries with limited cultural infrastructure continue to struggle. This highlights the need for global cooperation and development-focused cultural policies, especially through UNESCO and regional cultural funds (Mammadova & Abdullayev, 2025).

4.5 Policy Implications and Future Directions

Given their demonstrated economic contributions, theatre and cinema deserve greater recognition in national economic development plans. The following policy recommendations emerge from the findings:

1. Increased Public Investment: Governments should allocate consistent funding to support production, infrastructure, and training programs in the arts (Sadikhova, 2024).

2. Tax Incentives and Subsidies: Film and theatre producers should benefit from tax credits, especially for projects that boost tourism or employment.

3. Creative Education: Incorporating arts education at all levels ensures a sustainable talent pipeline and improves cultural literacy.

4. Digital Infrastructure Support: Especially in low-income countries, investments in broadband, streaming technology, and copyright protections are needed.

5. Cultural Tourism Development: Governments should invest in promoting film locations and theatre districts as tourist destinations.

6. Data Collection and Research: A lack of reliable data on the creative economy, especially in the Global South, hampers strategic decision-making. Improved statistical frameworks are essential.

Finally, international collaboration can play a vital role. Cross-border co-productions, cultural exchange programs, and regional networks can enhance the competitiveness and diversity of global cinema and theatre.

5. CONCLUSION

Theatre and cinema, traditionally viewed through the lens of cultural enrichment and artistic expression, have emerged as strategic economic assets with far-reaching impacts. This study highlights that these creative industries contribute significantly to GDP, employment, tourism, and innovation, making them indispensable to national and global economic ecosystems.

Quantitative data confirm the robust economic output of theatre and cinema across various regions—from Broadway's multibillion-dollar contributions to New York City's economy to the rapidly growing film sectors in emerging markets like Nigeria and South Korea. In addition to direct financial returns, these industries generate widespread indirect benefits, fostering job creation in hospitality, transport, retail, and technology. The arts also serve as a driver of urban regeneration, with theatre and film districts often acting as magnets for investment, cultural engagement, and community development. National foods and clothing can also be demonstrated in the film (Javid & Sadikhova, 2025)

Importantly, theatre and cinema offer unique value in the post-pandemic recovery era. While COVID-19 exposed vulnerabilities—particularly for live performance sectors—it also accelerated digital transformation, expanding access and creating new monetization models. The pandemic

served as a catalyst for innovation, pushing theatres and cinemas toward hybrid formats, global streaming, and interactive experiences, which are now reshaping the industry's future.

Yet, despite their clear economic benefits, these sectors remain underrepresented in policy and economic planning, particularly in developing countries. This underinvestment limits their growth potential and ignores their role in fostering cultural identity, soft power, and social cohesion. As such, there is an urgent need for integrated policy frameworks that treat theatre and cinema not as luxury sectors, but as essential components of economic development, innovation strategy, and education systems.

Looking ahead, governments, investors, and development agencies must prioritize sustainable investment in creative industries, promote equitable access, and protect creative labor rights. Enhancing data collection, facilitating international cooperation, and embedding creative economy strategies in urban and rural planning are also essential steps forward.

Furthermore, future research should explore the longitudinal impacts of theatre and cinema investments, the role of artificial intelligence and immersive technologies in reshaping audience engagement, and the social value of creative expression in divided societies. Only by acknowledging both the economic and cultural significance of these industries can we fully harness their power to build more resilient, inclusive, and creative economies in the decades ahead.

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