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EDITORIAL

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PREFACE

Dear Readers, We are pleased to present the latest issue of our scholarly journal, which brings together the results of interdisciplinary research aimed at understanding the historical stages in the development of science and technology, technological innovations, and their impact on society. This publication continues our commitment to fostering dialogue between historians, engineers, scientists, and cultural theorists, offering a platform for rethinking the intersections of knowledge systems across time and disciplines. By highlighting both well-established and emerging fields of inquiry, we strive to demonstrate the enduring relevance of historical analysis in addressing contemporary challenges.

This issue reflects our belief that science and technology are not only engines of progress but also complex cultural phenomena. Each article invites readers to explore how inventions, practices, and theories were shaped by – and in turn shaped – the societies in which they emerged. Through critical engagement with sources, methods, and narratives, we seek to illuminate the human dimension of scientific and technical change, encouraging reflection on its ethical, social, and philosophical implications.

The central focus of this issue is a fundamental study devoted to the work of Ukrainian geneticist Oleksii Sozinov (1930–2018), one of the key figures in 20th-century agricultural science. The article explores the development and implementation of phytotron technologies in plant breeding at the All-Union Selection and Genetics Institute (now the National Center for Seed Science and Variety Research). The authors not only reconstruct Sozinov's scientific career but also introduce a new array of archival sources into academic circulation, allowing for a reassessment of the innovative methods used to increase crop yields. This study convincingly demonstrates that an interdisciplinary approach – combining microhistory, source studies, history of science, and agrotechnology – can reveal the contributions of individual scientists to global transformations.

The theme of technological evolution continues with a timely study on the development of supercharging systems for piston aircraft engines. The authors meticulously reconstruct the chronology of these technologies, from the earliest days of aviation, focusing on technical innovations that significantly improved engine altitude performance. By combining technical analysis with historical context, the study offers insight not only into engineering features but also their impact on military aviation in the first half of the 20th century – a rare fusion of engineering precision and historical depth.

Another remarkable example of a technological breakthrough that influenced the course of history is radar technology during World War II. The related article discusses not only engineering solutions (such as Chain Home, Freya, SCR-270) but also the strategic role of radar in crucial battles including the Battle of Britain, the Atlantic campaign, and the Pacific theater. The authors also examine how the postwar development of radar influenced air defense systems, meteorology, and modern navigation. This analysis shows that technical innovation can become a bifurcation point in history – impacting both military strategy and civil progress.

The history of medicine is represented by an engaging comparative study of medieval Georgian medical culture and European practices. Special attention is given to the treatise *Ustsoro Karabadini*, which reveals the influence of Greco-Roman traditions on Georgian medicine. The article explores the four humors theory, dietary advice, childcare approaches, and seasonal diagnostics, offering a comprehensive view of the scientific culture of the time. It also highlights parallels between agricultural traditions, viticulture, and medical knowledge in Georgia and Europe, showing deep integration of cultural knowledge with natural medicine.

A completely different dimension of scientific progress is reflected in the review of the evolution of forensic bloodstain analysis. From visual inspection to the use of AI, this evolution mirrors the broader trend of science digitalization. The article traces how modern methods – such as spectroscopy, hyperspectral imaging, chromatography, and machine learning algorithms – enable accurate determination of stain age, opening new frontiers for forensic science. Despite these advances, the authors emphasize ongoing challenges such as standardization, environmental factors, and substrate differences. This study stands at the intersection of bioinformatics, analytical chemistry, and law.

Among contemporary issues, cybersecurity receives particular attention. The article on computer viruses provides a historical overview from the legendary Morris Worm to WannaCry, showing how technical threats became the subject of scientific inquiry. The focus is on the evolution of countermeasures: from signature-based antivirus software to machine learning, behavioral models, and deep neural networks. The study underscores the dual nature of this field: increasing complexity of threats alongside constant improvements in AI-based defense. The authors argue that the future of cybersecurity lies in the synthesis of historical experience and technological adaptability.

In the following article, the Authors presents an interdisciplinary study combining historical analysis and experimental research to examine the vulnerability of military drones made from carbon fiber-reinforced polymer (CFRP) to laser destruction. It explores the historical development of CFRP use in military drones, highlighting its adoption due to the need for lightweight, durable, and radar-evading materials, influenced by geopolitical and technological factors. Concurrently, the study investigates the rise of high-energy laser systems as precise countermeasures against fast, small, and stealthy drones, driven by concerns over swarm attacks and limitations of traditional defenses. Experimentally, CFRP samples were tested under controlled laser radiation to identify damage mechanisms and energy thresholds causing material failure. By integrating historical context with laboratory results, the article offers a comprehensive view of how past material choices have created current vulnerabilities and how modern laser weapons exploit these weaknesses, advancing more effective counter-drone strategies for present and future military applications.

This article examines the design, fabrication, and long-term operation of Kyiv's Evgeny Paton Bridge, the world's first all-welded highway bridge completed in 1953. Named after welding pioneer Evgeny Paton, the bridge marked a key advance in civil engineering and Soviet postwar reconstruction, showcasing the shift from riveted to welded structures through innovations in metallurgy, structural analysis, and automatic submerged arc welding. Using archival and technical sources, the study places the bridge within its political and economic context, highlighting its dual role as functional infrastructure and a symbol of Soviet scientific progress. The article reviews over seven decades of operational experience, focusing on the bridge's durability, maintenance, and influence on later engineering worldwide. Serving as a living laboratory, the Paton Bridge demonstrates the practical application of scientific research in welded steel structures and remains relevant to modern infrastructure and engineering education.

A study of the electrification of Tashkent from 1914 to 1918 presents significant historical interest. Against the backdrop of geopolitical instability and the colonial approach of the imperial center, the development of energy infrastructure in the region appears as an attempt at modernization despite unfavorable conditions. While the number of power stations increased, a lack of industrial support and investment outflow hindered further progress. The analysis reveals how energy policy influenced the region's economic potential and exposed untapped infrastructural resources.

Traditional technologies that have retained their relevance are highlighted in the article on wood-fired kiln ceramics. This topic offers a fresh interpretation of technology as a form of aesthetic and emotional experience. The authors trace the evolution of the practice from utilitarian craft to a philosophy of fire interaction. An analysis of kiln types, firing regimes, ash impact, and temperature variations helps explain why this technique continues to inspire contemporary artists.

A fascinating socio-technical case study is the history of automotive engineering in Francoist Spain. Through the lens of the *Revista de la STA*, researchers uncover the image of the engineer as a bearer of technical progress within an authoritarian state. Technological breakthroughs described by engineers themselves are presented as part of a collective imagination – a space where technology, the state, and professional pride coexist in a complex dynamic. This study demonstrates how cultural history shapes the history of technology.

Finally, the issue concludes with a study on the emergence of cinema as a technical and social phenomenon. It captures the transition from optical illusions and mechanical devices to digital technologies and virtual reality. The authors examine not only the technical foundations of cinema-mechanics, vision physiology, photochemistry – but also its cultural contexts: fairs, cinemas, and the public consumption of visuality. Cinema emerges as both a product of scientific knowledge and social demand, a communicative platform, and a technological system.

Taken together, this issue is a vivid illustration of the current state of historical and scientific studies. The articles transcend traditional disciplinary boundaries, rethink the human role in technical transformations, and emphasize the importance of local contexts in global processes. A shared feature across all contributions is the blend of historical depth, source-based rigor, and interpretive boldness. We are confident that these articles will be of value to researchers, educators, students, and all who are interested in the development of science, technology, and culture.

We also wish to express our sincere gratitude to the authors, reviewers, and editorial team whose dedicated work made this issue possible. Their intellectual contributions and commitment to scholarly excellence ensure that each article meets the highest academic standards. We are equally grateful to our readers, whose interest and feedback continue to inspire us to expand the scope and depth of our publication.

As we turn the pages of this issue, we invite you to join us in exploring the intricate connections between past innovations and present realities. We hope that these studies will not only inform but also provoke new questions, spark dialogue, and encourage further research. May this issue serve as a valuable resource and a catalyst for deeper understanding of the ways in which science, technology, and culture shape – and are shaped by – each other through time.

HISTORY OF SCIENCE

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Megaproject on innovative transformation of the plant breeding system to increase productivity and yield (second half of the twentieth century)

Abstract.*The purpose of the article is to reconstruct the events and analyze the scientific activities of the geneticist Oleksii Sozinov (1930–2018) aimed at the development of agricultural science in Ukraine. Particular attention is paid to the creation and development of the phytotron at the All-Union Breeding and Genetic Institute (now the Breeding and Genetic Institute – National Center for Seed and Variety Studies) in the second half of the twentieth century. The innovative transformation of the plant breeding system initiated by O. Sozinov, aimed at increasing the productivity and yield of agricultural crops, is studied. The use of methods of microhistory and comparative historical analysis allowed to reveal more deeply the scientific contribution of the scientist and his influence on the development of breeding science and technology. Based on the processing of archival materials, a set of sources was first introduced into scientific circulation, which allows us to rethink the importance of the developments of O. Sozinov and his colleagues in the creation and functioning of the phytotron. The analysis of documentary materials of the State Archives of Odesa Region and other sources allowed to expand the understanding of the use of phytotron technologies in breeding activities and their impact on agricultural science and crop yields. The contribution of O. Sozinov to the development of scientific research in the field of breeding and genetics, in particular the introduction of advanced experimental methods and the use of phytotron for research on grain crops, is outlined. It is proved that the scientist's many years of experience in plant breeding and genetics became the basis for the formation of long-term scientific directions in this field. The experimental approaches he introduced contributed to the innovative transformation of the breeding system, which ensured a significant increase in crop productivity and yield. It is concluded that the scientific achievements of O. Sozinov* *not only laid the foundation for further research, but also determined the prospects for the development of the industry for decades to come. The use of the phytotron has significantly expanded the possibilities of studying the influence of various factors on plant growth and development, which, in turn, has contributed to the creation of new highly productive varieties.*

Keywords: *Oleksii Sozinov; plant breeding; phytotron; genetics; agricultural science; innovative transformation*

Introduction.

The development of agricultural science in the second half of the twentieth century was marked by an active search for innovative approaches to increasing the productivity and yield of crops (Strelko, Pylypchuk, O. Ya, & Pylypchuk, O. O., 2024). One of the key areas was the introduction of the latest breeding methods based on the use of controlled plant growing conditions. In this context, the megaproject of Academician Oleksii Sozinov (1930–2018), aimed at the innovative transformation of the breeding system using phytotronic technologies, deserves special attention.

Accelerating the crop breeding process remains one of the priorities of modern agricultural science. Artificial climate technologies play a decisive role in this, as they can significantly shorten the plant growing season and produce several harvests of grain and other crops during a calendar year.

Internationally, the development of phytotronic technologies began in the mid-twentieth century. In the United States and Europe, institutions such as the Beltsville Agricultural Research Center (USA) and the Max Planck Institute for Plant Breeding (Germany) pioneered the introduction of controlled environments for crop experiments. Research at these centers has shown that the use of phytotrons can reduce the breeding cycle from 10−12 years to 4−5 years, which has become a significant breakthrough in agricultural science.

Canadian and Japanese scientists also made a significant contribution to the development of the phytotron concept. In particular, in Canada, the National Research Institute of Agriculture has developed methods for precise control of the photoperiod to improve the growth of grain crops.

In the world scientific literature, the development of plant breeding technologies in the second half of the twentieth century is viewed through the prism of technological innovations, the use of controlled conditions for growing plants, and genetic methods of increasing yields. The phytotron as a breeding tool played a significant role in accelerating the development of new varieties of cereals, vegetables and industrial crops.

V. Dubovyi notes that research on the problem of studying the growth and development of cereal crops in an artificial climate has been going on for more than 40 years (Dubovyi, 2020). Analyzing the results of scientific works, especially those conducted in the period 1978–1990, it becomes obvious how accessible this engineering and biological method was. In particular, when the cost of 1 kWh of electricity was only 1 kopeck, the use of an artificial climate made it possible to significantly speed up the breeding process. This made it possible to obtain up to five reproductions of spring wheat and barley, as well as three reproductions of winter cereals, which contributed to more efficient improvement of agricultural technologies and increased crop productivity (Downs, 1975).

Donald N. Duvick focuses his research on the use of controlled conditions for accelerated breeding and considers plant breeding using biotechnology primarily as a tool to improve the efficiency of traditional plant breeding, with a particular focus on increasing resistance to diseases and insects or adding new types of herbicide resistance. He notes that more and more attention is being paid to the potential of using biotechnology to create new industrial and food products based on plants (Duvick, 2009).

In his work, W. Gottschalk investigates the effect of temperature on flowering of Pisum plants using a phytotron. They studied 17 mutants and 20 recombinants under three temperature conditions. Low temperature (12.5 °C) significantly delayed flowering, but the genotypes differed from each other. High temperature (25 °C) had a negative effect on fasciate genotypes. None of the plants bloomed at either constant low or high temperatures - they need a change of low and high temperatures for normal flower formation. Studies confirm that most genotypes have specific temperature responses (Gottschalk, 1985).

J. Braak and L. Smeets provide a detailed description of the physiology laboratory, which includes a complex of greenhouses and specialized experimental rooms. The authors emphasize the conditions where researchers can control the main climatic parameters, including temperature and humidity, as well as regulate the duration and intensity of lighting, which allows them to create optimal conditions for scientific experiments. Special attention is paid to the technical aspects of microclimate control systems and their efficiency. The results of three years of experience in managing temperature and humidity conditions are summarized, which made it possible to assess their impact on the course of physiological processes in plants (Braak & Smeets, 1956).

The T. Tibbitts and T. Kozlowski (eds.) guidelines allow to: standardize methods of growing and analyzing plants in laboratory and greenhouse conditions; determine the optimal parameters of the environment for plant growth and development; conduct experiments on the influence of various factors (lighting, temperature, humidity, soil composition, etc.) on the physiological and morphological characteristics of plants; evaluate the effectiveness of fertilizers, growth regulators and other agrochemicals; develop recommendations for optimizing cultivation conditions to increase yield and quality (Tibbitts & Kozlowski, 1979).

Downs gives advice on flow and density in phytotrons (Downs, 1988). Other researchers pay attention to light (Biggs et al., 1971).

In Ukrainian and Soviet scientific literature, O. Sozinov's megaproject was seen as one of the key steps in the modernization of agricultural science in the USSR. The phytotron, created in the second half of the twentieth century, became the basis for the development of new crop varieties. Breeding technologies and methods were improved, which contributed to the efficiency of growing highly productive and resistant to unfavorable conditions varieties.

Sokolov notes that in the 70s of the last century, the world's largest phytotron was built, which made it possible to conduct research at a high scientific level regardless of the growing season (Sokolov, 2012). In addition, the author emphasizes that O. Sozinov's innovative research has always been characterized by the work of the Department of Genetic Basis of Breeding (Sokolov, 2012, p. 355).

Revealing the multifaceted figure of O. Sozinov, V. Vergunov notes "...the largest artificial climate station in the USSR, the phytotron, built during Sozinov's directorship, made it possible to significantly accelerate the breeding process." Thanks to the favorable conditions for scientific research and the talented leadership of O. Sozinov, young scientists were able to make world-class discoveries. A striking example of this is the achievement of his student, Corresponding Member of the National Academy of Sciences of Ukraine, State Prize winner O. Rybalka. He recalled that the results of his PhD thesis allowed them to be two years ahead of researchers from the University of Cambridge, having carried out the first mapping of the locus that encodes the biosynthesis of gluten proteins. Such breakthroughs seem almost unattainable in today's environment (Vergunov, 2018).

The scientific achievements of O. Sozinov (Sozinov, 1981b) became the basis for the development of modern breeding science in Ukraine, and also contributed to the integration of domestic research into the international scientific space.

The analysis of the literature shows that O. Sozinov's mega-project on the innovative transformation of the plant breeding system has made a significant contribution to the world and national agricultural science. The use of phytotrons has significantly accelerated the process of creating new varieties, increasing their resistance to adverse factors and, consequently, their yield.

The phytotron as a complex for artificially regulating plant growth conditions has opened up new opportunities for the development of the breeding process, increasing the efficiency of experiments, and creating new highly productive varieties. However, despite its significant contribution to the development of agricultural science, research into the history of this project remains undercovered.

The relevance of this topic is due to the need to rethink the scientific achievements of the past and their impact on modern agricultural technologies. The study of O. Sozinov's megaproject allows not only to assess the scientist's contribution to the development of breeding, but also to understand the prospects for the further use of phytotronic technologies in the world agricultural practice.

Methods and Materials.

The study is based on the principles of historicism and objectivity, which allowed us to reproduce with maximum accuracy the real historical picture of the implementation of O. Sozinov's project on the innovative transformation of the plant breeding system to increase productivity and yield. The use of the problem-chronological method allowed us to find out the reasons for the formation of established methods of conducting experimental work within this project, and the retrospective method allowed us to show the patterns of this process. The chronological method was used to achieve the appropriate sequence of presentation of the historical information obtained, and the methods of logic, analysis and synthesis were used to draw the conclusions and provisions set forth in the article.

Results and Discussion.

In the second half of the twentieth century, the development of genetics in Ukraine took place in the context of the restoration of science after Stalin's repressions and the influence of official ideology.

In the 1950s and 1960s, the All-Union Breeding and Genetic Institute (ABGI) (now the Breeding and Genetic Institute – National Center for Seed and Variety Studies) was the center of the revival of genetics after the Lysenko period, and it became one of the key centers for the development of genetic research in the USSR. The Institute actively contributed to the restoration and development of modern genetic science, in particular, the study of molecular biology, plant and animal genetics, and crop breeding.

With the arrival of O. Sozinov, a new, dynamic stage in the life of the All-Ukrainian Scientific and Research Institute began. As a representative of the command-and-control system (in its best manifestation), he perfectly met its requirements. He was characterized by an authoritarian style of management, but at the same time demonstrated high efficiency, determination in decision-making and a desire for development. Under his leadership, favorable financial and organizational conditions were created for the work of employees (State Archives of Odesa Oblast. Fund P. 3139, Inventory 1, Case 44, Sheet 63), which contributed to the growth of the institution to a world-class level.

One of the key areas of his activity was to engage specialists in various fields – mathematicians, engineers, and representatives of related sciences – in cooperation. This contributed to the development of scientific areas that were important for the country's economy, led by him. In particular, a significant achievement was the creation of the phytotron, a unique agrobiological research complex that allowed monitoring of cultivated plants at all stages of their development, accumulating and processing huge amounts of information. This, in turn, brought agrobiological science to a qualitatively new level. It is thanks to the strategic vision and focused policy of O. Sozinov that the Institute received a new impetus for development, strengthening its position as one of the leading research centers.

After the period of dominance of the Lysenko theory, which denied the foundations of classical genetics, the Institute's scientists continued to develop new methods and approaches to the study of genetic processes. Scientists actively applied the achievements of world science, in particular, O. Sozinov, looking for new opportunities for the development of genetics and plant breeding, considered the phytotron as an innovative tool. It should be noted that a similar center had already been established in Germany using a phytotron, and its work was much more effective than the activities of the Department of Plant Production and Breeding of the GDR Academy of Agricultural Sciences (Dragavtsev, 2000).

After defending his PhD thesis, O. Sozinov worked under the supervision of Academician F. G. Kirichenko, learning the methods of barley breeding by

P. H. Garkavy and mastering the peculiarities of wheat breeding. He took an active part in the life of the institute's staff, holding the position of a collective boss, constantly spoke at postgraduate seminars and made numerous trips to rural regions. In 1961, at the suggestion of the director of the institute, O. Musiyko, he headed the grain quality laboratory. From the very first steps, he had to restore the operation of outdated equipment, organize its repairs, develop new methods and establish cooperation with breeders. The laboratory has become a recognized scientific and methodological center for grain quality in the former USSR. The laboratory's activities were not limited to preparing and holding union seminars and methodological meetings, but also included publishing methodological materials and organizing joint research with scientists from Moscow, Omsk, Kharkiv and other research centers (Vergunov et al., 2010, p. 24).

Between 1961 and 1971, when Oleksii Sozinov served as deputy director for scientific work at the All-Union Scientific Research Institute, he was able to implement large-scale changes aimed at overcoming the remnants of Lysenkoism in science. Thanks to his convictions and efforts, he was able to influence the director of the institute, O. S. Musiyko, and prove the importance of these changes for the further development of breeding science. In particular, the construction of a phytotron, which will allow controlling key environmental parameters such as temperature, humidity, lighting, and atmospheric composition. These conditions make it possible to accelerate plant growth, study their response to various factors, and conduct experiments to improve yields.

Construction of the phytotron began in 1967 and lasted ten years. However, the official opening of the facility was scheduled for the fall of 1978, due to the need to fully load all freezers with experimental material. This made it possible to ensure that the complex was ready for scientific research in optimal conditions (State Archives of Odesa Oblast. Fund R. 7881, Inventory 1, Case 152, Sheet 137–143).

Already on January 10, 1978, the Academic Council of the All-Ukrainian Scientific Institute, headed by O. O. Sozinov, approved a program of research on the phytotron (State Archives of Odesa Oblast. Fund P. 3139, Inventory 1, Case 68, Sheet 32). It is important to note that its development took into account international best practices in the field of phytotron research. In particular, the achievements of French scientists in the field of plant physiology, Australian scientists in the study of drought resistance, and Japanese scientists in plant reproduction were used (State Archives of Odesa Oblast. Fund R. 7881, Inventory 1, Case 152, Sheet 27).

This integrated approach has allowed us to create a scientifically based program aimed at improving plant breeding and genetics.

The complex consisted of three parts: a laboratory building, a technical block with greenhouses, and a block of climatic chambers. Built according to the original design, the complex was intended for genetic and breeding research in a wide range of temperatures and had 14 freezers (State Archives of Odesa Oblast. Fund R. 7881, Inventory 1, Case 152, Sheet 137–143).

The climatic chambers of the phytotron differed in their purpose, the range of adjustment of the main environmental parameters, and design features. Ten chambers with natural light were arranged in two tiers at different height levels. Each of the tiers was a single building structure divided by glass partitions into five separate chambers, each with a floor area of 18 m².

The upper tier was equipped with double glazing, which allowed the temperature to be maintained between +15 and +35 °C. In the lower tier, where lower temperatures were required, triple glazing was used. The temperature regime here ranged from +5 to +25 °C. One of the chambers in the lower tier had the ability to create negative temperature values, which ensured that experiments could be conducted under artificial cooling conditions.

The stability of the microclimate in each chamber was maintained by autonomous air conditioners equipped with freon refrigeration units, which guaranteed precise temperature control in accordance with the research requirements.

In addition to the main climate chambers, the phytotron also had vegetation chambers and climate cabinets. They differed mainly in size, but had similar air conditioning systems that operated on a single-acting principle. The range of temperature control in these chambers was wider and ranged from +4 to +45 °C, which allowed for experiments in different climatic conditions (Sozinov, 1978b).

O. Sozinov realized that the introduction of the latest technologies in breeding should be accompanied by fundamentally new results that would be a breakthrough in the genetic field. To achieve this goal, it was necessary to conduct specialized scientific research, which was already being actively carried out and planned for the future. In particular, methods were developed to shorten the vernalization period of winter crops, and the optimal parameters of temperature, light exposure, and supply of plants with the necessary nutrients were determined.

Given the high cost of phytotron space, it was extremely important to plan experiments rationally and analyze the results in depth. For this purpose, it was necessary to apply mathematical methods of data processing. Quantitative characteristics of a number of key properties of genotypes have already been proposed, including competitiveness, environmental plasticity, response to improved growing conditions, etc. That is why, in addition to breeders, mathematicians were actively involved in the work in the phytotron (State Archives of Odesa Oblast. Fund R. 7881, Inventory 1, Case 152, Sheet 139), which made it possible to increase the efficiency of research.

One of the main tasks of the latest breeding technologies was to create varieties and hybrids characterized by comprehensive resistance to diseases and pests. Achieving success in this area largely depended on a detailed study of pathogens, determining their racial composition, and the effective selection and use of donors in the hybridization process. Other important factors were a deep understanding of the genetic mechanisms of field resistance of plants and providing an optimal background for the precise selection of genotypes that demonstrate high resistance to disease.

In the climatic chambers of the phytotron, scientists conducted in-depth research on cereal diseases, including brown leaf and stem rust, powdery mildew, smut, helminthosporiosis, viral infections, and other pathogens. Particular attention was paid to the study of pathogen genetics, their notypical composition, adaptation mechanisms, and the prediction of new races. At the same time, the resistance of different varieties of wheat and barley to these diseases was studied, which is critical for maintaining grain yields and quality.

A separate area of research was devoted to studying the mechanisms of field resistance of grain crops to various pathogens and pests. In particular, attention was focused on the resistance of plants to rust fungi, powdery mildew, and viral infections, as well as their ability to resist cereal flies, aphids, moths, and other pests. O. Sozinov, together with other scientists, conducted a comprehensive identification of genes responsible for plant resistance, studied the conditions of their manifestation and the patterns of inheritance in the process of hybridization (Ursu, 2013).

This contributed to the development of new high-yielding varieties with a broad genetic basis and comprehensive immunity to biotypic variability of pathogens.

In addition, a thorough phytopathological assessment of wheat and barley breeding material was carried out in the climatic chambers of the phytotron. The tests included analysis of resistance to yellow rust, viral diseases and damage caused by pests. The use of the phytotron significantly accelerated the breeding process, as it allowed for several generations of full-grown plants within a year, which made it possible to perform complex crosses for resistance breeding more efficiently. This has led to the accelerated development of new varieties that can adapt to changing growing conditions and the impact of pathogens.

In the second half of the twentieth century, breeding research aimed at improving the immunity of crops focused on creating new donors with comprehensive resistance to adverse conditions and high economic value. It was especially important to develop winter wheat and barley varieties that would combine resistance to rust, powdery mildew, and low temperatures. However, such genotypes were extremely rare in the wild, which complicated the breeding process.

The use of climatic and freezing chambers greatly expanded the capabilities of breeders, allowing them to select the most promising samples in a targeted manner. These technologies provided for a comprehensive study of breeding material that was grown in a phytotron and simultaneously tested in several ecologically different regions. Field experiments, even with the use of artificially created climatic conditions, remained a key stage of research, as they provided the most reliable assessment of genotype behavior in the real environment.

At the same time, the use of the phytotron significantly increased the efficiency of breeding. It complemented field research by providing a comprehensive assessment of the adaptive potential of plants and allowing unsuitable genotypes to be rejected before they were tested in the field. This approach helped to accelerate the process of creating promising varieties with high resistance to biotic and abiotic stress factors.

O. Sozinov proposed a system of symbols for allelic blocks and a methodology for recording genetic varietal prolamine formulas. The scientist's research has confirmed that certain allelic blocks not only determine the technological properties of grain, but also have a connection with frost resistance, disease resistance, and other agronomically important traits. Since the electrophoretic analysis of prolamines is independent of growing conditions, the identification of varietal formulas can be performed on grain grown under controlled conditions (phytotron, greenhouses). One or even half a grain is sufficient for the analysis, making this method extremely efficient and affordable. At the same time, new genetically determined differences between genotypes were identified, including their specific responses to different parts of the solar spectrum. This opened up new perspectives in the study of photosensitivity mechanisms and their impact on plant growth, development, and productivity, which is of great importance for crop breeding and adaptation to climate change.

Since the opening of the phytotron, most of the scientific research in Odesa region has been conducted on its basis. Thanks to the introduction of modern technologies, plant breeders have expanded the range of research methods, actively using cultures of plant cells, tissues and embryos. Particular attention was paid to the cultivation of embryos, which opened up new opportunities for obtaining distant hybrids and creating haploid genotypes (State Archives of Odesa Oblast. Fund R. 7881, Inventory 1, Case 152, Sheet 141), which, in turn, became a key tool in solving the problem of homozygosity of breeding material and the identification of promising homozygous amphiploids that are highly valuable for breeding and further improvement of crops.

The second half of the twentieth century saw a real revolution in the biological sciences, particularly in the field of genetics, driven by the development of transformation and transgenesis technologies, the process of transferring genetic information at the DNA level. Although at that time there was not yet sufficiently convincing evidence of the possibility of successful transgenesis in higher plants, this research was actively developing. This was due to the assumption that genetic engineering methods could have a significant impact on breeding, opening up new perspectives in creating plants with valuable economic traits.

A prominent Ukrainian scientist, O. Sozinov, was one of the leading proponents of this area of research. He believed that progress in molecular biology would facilitate the rapid detection and identification of valuable genes, which, in turn, would be of great importance for practical breeding. The scientist emphasized the importance of studying the mechanisms of gene interaction in the genetic system of organisms, especially under conditions of controlled cultivation (State Archives of Odesa Oblast. Fund P. 3139, Inventory 1, Case 68, Sheet 30–34). He saw in these studies not only fundamental value, but also direct applied value for improving breeding methods.

O. Sozinov identified two key areas of such research. The first one concerns the study of genetic interactions within pairs of alleles, taking into account their pleiotropic effect. In particular, it is about establishing the patterns of so-called “floating dominance” and identifying factors that affect the degree of dominance of traits in hybrid plants depending on growing conditions. This made it possible to predict when full dominance, intermediate dominance, variability, or overdominance would occur. The second direction is aimed at studying inter-allelic interactions in polygenic systems that determine quantitative traits. Particular attention was paid to the effects of additive, dominant, and epistatic gene effects, with additive action playing a key role. It largely determines the level of the coefficient of inheritance of traits and affects the efficiency of the breeding process (Sozinov, 1978b, p. 111). Thus, the development of genetic engineering and in-depth study of the mechanisms of genetic interactions have opened up new opportunities for improving cultivated plants, which has become the basis of modern approaches in breeding and agricultural biotechnology.

An important stage in the institution's activities under O. Sozinov's leadership was overcoming the isolation from world science, which had long hindered its development, contributing to provincialism and technological lag. Realizing the need to integrate into the international scientific space, O. Sozinov made significant efforts to establish cooperation with the world's leading scientific centers. However, the first steps in this direction were made in 1966–1970, when the party bureau decided to approve the characteristics for foreign business trips of researchers (State Archives of Odesa Oblast. Fund R. 7881, Inventory 1, Case 294, Sheet 35). This became the starting point for active international knowledge exchange, which allowed researchers to establish contacts with leading foreign institutions, adopt best practices, and introduce modern methods into domestic breeding. Subsequently, the Institute expanded the scope of cooperation by concluding agreements with scientific institutions in Europe and America (State Archives of Odesa Oblast. Fund P. 3139, Inventory 1, Case 59, Sheet 28), organizing joint research, international conferences and internships. This contributed to the introduction of innovative technologies in the breeding process, raising the level of domestic agricultural science and strengthening the Institute's position in the global scientific arena. It is worth noting that, according to the decision of the 25th session of the Council for Mutual Economic Assistance (CMEA), the All-Ukrainian Agricultural Institute under the leadership of O. O. Sozinov was transformed into a focal point for the development of theoretical principles of breeding and seed production, as well as the creation of high-yielding varieties and hybrids of crops for CMEA member countries.

Odesa received hundreds of samples of wheat, barley, and other crops from all CMEA member countries, which facilitated active international exchange of genetic material. In one of the world's largest phytotrons, these samples were sown in a quarantine nursery, where they underwent careful adaptation and evaluation. Later, the best of them were used to create new varieties and hybrids that met the agroclimatic conditions of both Ukraine and other CMEA member states (Lyfenko, 2012). The Institute's activities were of strategic importance for the development of agriculture, as it provided countries with highly productive seed material, which helped to increase yields and food security in the region.

The history of the successes of the phytotron and the All-Union State Institute of Agriculture, recognized at the level of the USSR, can be documented in the events that took place from the beginning of Sozinov's project to the last year of the scientist's stay in Odesa. In particular, on August 21, 1978, at the XIV International Genetic Congress held in Moscow, the effectiveness of the phytotron at the All-Union State Institute of Genetics was highly appreciated. The participants of the event noted the significant contribution of the institution to the development of genetic research, emphasizing the role of the phytotron in conducting experiments on plant breeding and improvement (Sozinov, 1978a).

On December 6–7, 1978, at the session of the General Meeting of the USSR Academy of Sciences, O. Sozinov presented the results of research that confirmed the effectiveness of using the phytotron in studying the genetic characteristics of plants. The contribution of the All-Union Agricultural Institute specialists to the improvement of breeding methods based on the use of phytotronic technologies was particularly noted, which opened up new prospects for genetic research and increased crop yields (Sozinov, 1979a; 1979b).

In 1980, the city of Hamburg hosted a scientific forum on security and cooperation in Europe. The event brought together leading specialists, scientists and experts from different countries to discuss topical issues of science and technology development. One of the highlights of the forum was a presentation by O. Sozinov, who highlighted the achievements in the field of scientific research using phytotron, focusing on the prospects of using this technology to improve the efficiency of agricultural production and study physiological processes in plants under controlled conditions. The participants of the event highly appreciated the contribution of the phytotron, which operated at the All-Ukrainian Agricultural Institute, noting its significant role in the development of agricultural science. They emphasized the importance of further research in this area and international cooperation to improve plant cultivation methods and ensure food security (Sozinov, 1981a).

In 1978, the Academic Council of the Institute nominated O. Sozinov for full membership in VASKhNIL. The Institute's submission stated: “O. O. Sozinov is widely known for his contribution to the development of the genetics of the protein complex of cereals. Since 1958, he has been working extensively on improving grain quality. Since 1971, he has been the director of the All-Union Breeding and Genetic Institute. In recent years, he has developed more than 30 new varieties, which are grown on an area of more than 10 million hectares, with a net profit of 588 million rubles.” To this figure was added another one - “...due to the introduction of Sozynov's varieties into production, the country additionally received 7201.1 thousand tons of grain (State Archives of Odesa Oblast. Fund P. 7881, Inventory 1, Case 152, Sheet 62–64).

In his early fifties, O. O. Sozinov became well known in Ukraine and abroad as an outstanding geneticist and science organizer. He was elected an academician of the Academy of Sciences of the Ukrainian SSR in the specialty of genetics and was awarded the highest state honors: the Order of Lenin (1973), the Order of the October Revolution (1977), and the Red Banner of Labor (1971).

At a meeting of the Institute's Academic Council on October 20, 1978, Director O. O. Sozinov announced that he had been appointed Vice President of the All-Union Academy of Agricultural Sciences and would simultaneously head the Laboratory of Biochemical Genetics of the Institute of General Genetics at the main academy of the country, the USSR Academy of Sciences (State Archives of Odesa Oblast. Fund P. 7881, Inventory 1, Case 152, Sheet 62).

Conclusions.

In the second half of the twentieth century, Ukrainian plant breeding science made a significant step forward through the introduction of the latest technologies and innovative approaches. Academician O. Sozinov played an important role in this process, not only by creating a powerful research center, but also by initiating the use of technologies unique for his time, in particular the phytotron. This made it possible to significantly speed up the breeding process, improve control over plant cultivation, and expand the possibilities of research in genetics and breeding.

The phytotron has become a revolutionary platform for testing and developing new crop varieties, which has significantly reduced the time required for breeding experiments. The use of a controlled environment has allowed scientists to explore the impact of climatic factors on plant development in greater depth, ensuring better adaptation to different environmental conditions. In particular, this contributed to the development of high-yielding varieties of wheat, corn, soybeans and vegetables, which became the basis for the further development of Ukraine's agricultural sector.

Despite its successes, the implementation of O. Sozinov's mega-project faced serious difficulties. The financial crisis that followed the collapse of the USSR led to the decline of research infrastructure, including the phytotron. The functioning of such a high-tech facility became impossible due to the lack of adequate funding and support from the state. This led to the loss of a unique tool that could have served as a basis for the development of modern genomics and biotechnology.

However, even in such circumstances, the scientific heritage of Academician Sozinov has not lost its relevance. His ideas and approaches to breeding research remain the basis for further developments in the field of agricultural science. The Phytotron demonstrated the prospects of creating controlled conditions for breeding, which in the XXI century has been continued in modern biotechnology laboratories and research in the field of genetic engineering.

Thus, O. Sozinov's megaproject not only made a significant contribution to the development of plant breeding in the second half of the twentieth century, but also left a significant scientific heritage that still influences the development of agricultural science and biotechnology in Ukraine and the world. And the development of breeding technologies based on the use of phytotrons was an important step in improving the efficiency of agricultural science in the second half of the twentieth century.

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The author declare no conflict of interest.

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Мегапроект з інноваційної трансформації системи селекції рослин для підвищення продуктивності та врожайності (друга половина XX століття)

Анотація. *Метою статті є реконструкція подій та аналіз наукової діяльності вченого-генетика Олексія Олексійовича Созінова (1930–2018), спрямованої на розвиток сільськогосподарської науки в Україні. Особливу увагу приділено створенню та розвитку фітотрону у Всесоюзному селекційно-генетичному інституті (нині – Селекційно-генетичний інститут – Національний центр насіннєзнавства та сортовивчення) у другій половині XX ст. Досліджено ініційовану О. Созіновим інноваційну трансформацію системи селекції рослин, спрямовану на підвищення продуктивності та врожайності сільськогосподарських культур. Використання методів мікроісторії та порівняльно-історичного аналізу дозволило глибше розкрити науковий внесок ученого та його вплив на розвиток селекційної науки і технологій. На основі опрацювання архівних матеріалів уперше введено в науковий обіг комплекс джерел, що дозволяють переосмислити значення розробок О. Созінова та його колег у створенні й функціонуванні фітотрону. Аналіз документальних матеріалів Державного архіву Одеської області та інших джерел дав змогу розширити уявлення про застосування фітотронних технологій у селекційній діяльності та їхній вплив на аграрну науку й підвищення врожайності сільськогосподарських культур. Окреслено внесок О. Созінова у розвиток наукових досліджень у галузі селекції та генетики, зокрема впровадження передових експериментальних методів і використання фітотрону для досліджень зернових культур. Доведено, що багаторічний досвід ученого у сфері селекції та генетики рослин став основою для формування довгострокових наукових напрямів у цій галузі. Запроваджені ним експериментальні підходи сприяли інноваційній трансформації системи селекції, що забезпечило суттєве підвищення продуктивності та врожайності сільськогосподарських культур. Зроблено висновок, що наукові здобутки О. Созінова не лише заклали фундамент для подальших досліджень, а й визначили перспективи розвитку галузі на десятиліття вперед. Використання фітотрону значно розширило можливості дослідження впливу різних факторів на ріст і розвиток рослин, що, своєю чергою, сприяло створенню нових високопродуктивних сортів.*

Ключові слова: *Олексій Созінов; селекція рослин; фітотрон; генетика; аграрна наука; інноваційна трансформація*

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Bloodstain in forensics: From visual inspections to AI-assisted pattern analysis and age estimation

***Abstract**. Bloodstains have long served as critical evidence in forensic investigations, providing insights into the timing and nature of violent crimes. This article traces the historical evolution of bloodstain analysis, from early visual inspection to the adoption of modern methods and technologies. Blood pattern analysis has now advanced into a systematic science and incorporated artificial intelligence technology, offering quantitative insights into the mechanisms of blood spatter. For age estimation of bloodstains, DNA analysis extracts temporal changes in genetic materials from degraded bloodstains. High-performance liquid chromatography further complemented bloodstain investigations by quantifying biochemical markers indicative of time since deposition. Spectroscopic methods, including Raman and infrared spectroscopy, have identified specific molecular vibrations associated with the temporal degradation of blood components, while optical techniques based on photon reflection, absorption, and fluorescence provide alternative pathways for estimating bloodstain age. Smartphone-based colorimetry has emerged as a cost-effective and portable solution, tracking the visible progression of blood color from bright red to dark brown over time. Moreover, hyperspectral imaging integrates imaging and spectroscopy, allowing spatially resolved age estimation by analyzing spectral data at the pixel level. This article highlights the historical progression and technological advancements that have shaped bloodstain analysis in forensic* *discipline. By integrating modern instrumentation with artificial intelligence technologies, the field continues to move closer to reliable on-site analysis. However, challenges such as environmental variability, substrate effects, and standardization remain. Continued research and validation are imperative to refine these methods and establish standardized protocols for forensic applications. This historical and technical overview underscores the transformative impact of interdisciplinary innovation on the evolution of bloodstain analysis, bridging the gap between laboratory research and practical forensic settings.*

Keywords: *bloodstain pattern analysis; age estimation; spectroscopy; hyperspectral imaging; smartphone colorimetry*

Introduction.

Blood comprises approximately 45% of the solid components, i.e., platelets, white blood cells, and red blood cells, suspended in plasma. Its physical properties, such as density, viscosity, and surface tension, are governed by its composition. Upon leaving the human body, blood notably undergoes coagulation and eventually drying. The transformation into a dry stain on the substrate is often accompanied by crack propagation. In forensic investigations, blood has long been regarded as vital evidence, aiding in crime scene reconstruction and including or excluding suspects or victims (Brodbeck, 2012; Das, Harshey, Nigam, Yadav, & Srivastava, 2020; Giulietti, Discepolo, Castellini, & Martarelli, 2023; Seki, Hsiao, Ishizawa, Sugano, &Takahashi, 2024; Stojanović, Stojanović, Šorgić, & Čipev, 2020; Stotesbury, Cossette, Newell-Bell, & Shafer, 2021).

The scientific blood detection in Figure 1 dates back to Ludwig Karol Teichmann's pioneering hemin crystal test in 1853 (Kerr & Mason 1926). The human bloodstains were verified by shape of hemin crystals extracted from a specimen under test. At the beginning of the 20th century, significant breakthroughs for forensic applications included the discovery of blood groups based on different types of red blood cells by Landsteiner (1901) and the introduction of the Kastle-Meyer test, which identifies bloods by the reaction between phenolphthalein hydrogen peroxide in the presence of hemoglobin (Glaister, 1926).

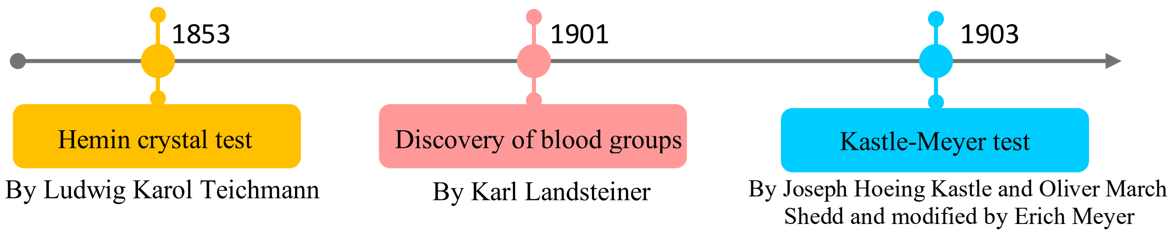

Figure 1. Significant milestones in the pioneering of blood detection methods (Authors' source).

The detection of blood initially relied on visual inspection. At crime scenes, the distinctive bright red blood and reddish-brown bloodstain are often visible, while residual blood, even when attempts have been made to remove it, can be revealed using Luminol sprays. Rudimentary chemical tests can distinguish blood from other reddish substances, also found at the place of crime (Edelman, Manti, van Ruth, van Leeuwen, & Aalders, 2012a). In the laboratory, more advanced tests can verify whether it is human blood and determine the blood group. Blood evidence's physical appearance is recorded in images and documents. For subsequent laboratory analysis, liquid blood is typically collected using a syringe and stored in tubes with anticoagulants. Alternatively, a fabric may be used to absorb blood. Dried blood samples are collected using tape, cotton-tipped applicators, or scrape-off blades. To prevent degradation, blood samples are refrigerated, and stained samples are dried before storage. After collection and preservation, forensic analysis plays a crucial role in extracting meaningful evidence. The introduction of forensic DNA analysis in the 1980s revolutionized criminal investigations, enabling precise identification of individuals. Since the early 2000s, techniques such as Polymerase Chain Reaction (PCR) and Short Tandem Repeat (STR) analysis have significantly expanded the use of DNA profiling in forensic science, supported by databases like the UK's National DNA Database and the USA's CODIS. More recently, advancements in artificial intelligence (AI) have been leveraged to automate forensic DNA profiling, enhancing efficiency and reducing human error.

Beyond blood detection, bloodstain pattern analysis and age estimation provide deeper insights into crime scene reconstruction. The shape, size, and distribution of bloodstains vary based on the nature of the incident, environmental conditions, and the substrate on which they are found (Das, Harshey, Nigam, Yadav, & Srivastava, 2020). For instance, analyzing bloodstains on porous fabric can be challenging, while outdoor stains are often significantly altered by environmental factors. Early investigations relied on visual inspection, categorizing stains as fresh, dry, or old based on their spatial distribution. Accurately estimating bloodstain age is crucial for reconstructing crime scenes (Weber & Lednev 2020). Various methods, including RNA degradation, electron paramagnetic resonance (EPR), oxygen electrode analysis, and chromatography, have been employed for precise age determination (Giulietti, Discepolo, Castellini, & Martarelli, 2023; Seki, Hsiao, Ishizawa, Sugano, &Takahashi, 2024). These techniques reveal that blood undergoes chemical and physical changes over time (Bremmer, Nadort, van Leeuwen, van Gemert, & Aalders, 2011; Cadd, Li, Beveridge, O'Hare, & Islam, 2018). However, despite their high accuracy, they require extensive sample preparation and time-consuming laboratory analysis (Li, Beveridge, O'Hare, & Islam, 2013). As alternatives, spectroscopic and colorimetric methods have gained prominence in bloodstain analysis. These non-contact methods allow for rapid, in-situ examination, making them highly valuable for forensic investigations (Bremmer, Nadort, van Leeuwen, van Gemert, & Aalders, 2011; Weber & Lednev 2020).

The purpose of this article is to trace the evolution of bloodstain analysis, from its early foundations to the emergence of artificial intelligence (AI)-assisted techniques for reliable on-site forensic investigations. By bridging laboratory research with practical forensic applications, this interdisciplinary review highlights key advancements shaping the field. The methodology for collecting and reviewing relevant literature are described in the next section. Section 3 examines the historical development and forensic importance of bloodstain pattern analysis. Section 4 examines key advancements in laboratory-based bloodstain age estimation techniques. Meanwhile, portable spectroscopic and colorimetric methods have emerged as promising tools for on-site applications. Section 5 focuses on portable optical and vibrational spectroscopy, colorimetry, and hyperspectral imaging, highlighting their recent advancements and ongoing developments in on-site bloodstain age estimation methodologies. Finally, Section 6 summarizes the discussed methodologies and provides an outlook on AI integration in forensic bloodstain analysis.

Methodology.

To investigate the historical development and current state of bloodstain pattern analysis and age estimation, a bibliometric analysis was conducted. A search was performed in the Scopus database using key terms: "bloodstain," "blood pattern analysis," and "blood age estimation." This search aimed to evaluate the dynamics of the scientific community's interest and the evolution of research trends in various aspects of forensic bloodstain analysis. After excluding irrelevant publications, 64 research articles were categorized into two main groups: bloodstain pattern analysis (Section 3) and bloodstain age estimation. The latter was further divided into laboratory-based methods (Section 4) and on-site spectroscopy and colorimetry (Section 5). Additionally, key references outside the Scopus database (e.g., books, websites) were cited for their relevance to the Scopus-indexed articles. The literature review placed particular emphasis on the advancing roles of smartphone colorimetry, hyperspectral imaging, and emerging AI-assisted methods in forensic investigations. The integration of these technologies was analyzed to provide a comprehensive overview of past developments, current challenges, and potential future directions in the field.

Bloodstain Pattern Analysis.

Bloodstain pattern analysis involves examining the shapes, sizes, orientations, locations, and distribution of blood residues at a crime investigation to reconstruct the physical occurrences that could have taken place (Bergman, Klöden, Dreßler, & Labudde, 2022; James, Kish, & Sutton, 2005; Zou & Stern, 2022). As shown in Figure 2, the first systematic approach was pioneered by Piotrowski (1895), where he explored the influence of various forces on the formation and distribution of bloodstains. Another landmark study was bloodstain trajectory analysis by Balthazard, Piedelievre, DeSoille, & DeRobert (1939). Bloodstain pattern analysis began to gain prominence in the 1950s, with the expert testimony of Paul L. Kirk on bloodstains being accepted as evidence in a US court for the first time in 1957 (EngagedScholarship @ Cleveland State University, 2024). The widespread adoption of these techniques was championed by Herbert Leon MacDonell, who wrote the book (MacDonell, 1972) and organized the first formal bloodstain training course in 1973. In 1983, a group of bloodstain analysts established the International Association of Bloodstain Pattern Analysts to further advance the field (International Association of Bloodstain Pattern Analysts, 2024). Over time, the technique has evolved into an essential forensic tool, though its accuracy and reliability have been under more scrutiny in the last decade (Smith, 2018).

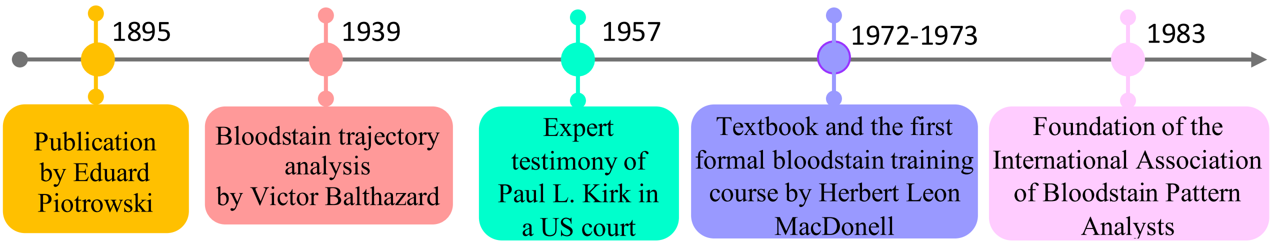

Figure 2. Significant milestones in the pioneering of bloodstain pattern analysis (Authors' source).

Bloodstains are typically classified into three groups, namely passive patterns, spatter patterns, and altered patterns (Singh, Gupta, & Rathi, 2021). Passive patterns are created by gravity and include blood pools, drip stains, flow stains, and serum stains (Singh, Gupta, & Rathi, 2021). Drip stains form as blood falls undisturbed, often taking a spherical shape unless affected by external forces. Depending on the angle of impact, these stains may appear as circular drops or elongated marks (SWGSTAIN, 2009). Spatter patterns consist of small, elliptical, or circular bloodstains created when blood is forcefully ejected, such as when a victim is struck by a hard object (James, Kish, & Sutton, 2005; Rough, Batchelor, Green, & Bainbridge-Smith, 2024). These patterns provide vital details regarding direction, velocity, and impact's origin. Altered patterns arise when bloodstains undergo physical or environmental changes, including diffusion, dilution, insect activity, or physical actions such as smearing (James, Kish, & Sutton, 2005). These patterns can obscure or modify the original blood evidence, complicating forensic interpretation.

Bloodstain patterns dispersed throughout a crime scene can be instrumental in event reconstruction, providing investigators with a comprehensive understanding of the events leading to the bloodshed. By systematically distinguishing and analyzing bloodstain patterns, forensic experts can identify informative features that shed light on the sequence of events (Comiskey, Yarin, Kim, & Attinger, 2016; James, Kish, & Sutton, 2005; Latham, 2024). Blood pattern analysis has been extensively applied to criminal investigations, leveraging common features such as stain morphology and pattern characteristics to uncover critical insights (Rough, 2024). For instance, a study of UK case files from 2012 to 2020 revealed prevalent attack techniques, weapons used, and the frequency of various bloodstain pattern classifications (Home, Norman, Palmer, Field, & Williams, 2022).

Blood pattern analysis methods commonly rely heavily on practical training acquired through workshops, trial-and-error approaches, and practitioner experience. However, empirical research has contributed significantly to refining and understanding the principles behind bloodstain pattern formation. For example, de Bruin, Stoel, and Limborgh (2011) highlighted the importance of larger, elliptical drops when determining the area of origin of bloodstains. Similarly, Comiskey, Yarin, Kim, and Attinger (2016) used a blood-soaked sponge to simulate back-spatter formation, accounting for factors such as air drag and gravity in their analysis of blood velocities. In another study, Singh, Gupta, and Rathi, (2021) utilized artificial bloodstains made with Awlata, an Indian dye, to investigate the correlations between stain properties and blood drop height. Their findings demonstrated that spine formation was inversely proportional to the height of the falling blood, while the distance of satellite stains increased with the drop height.

The classification of bloodstains often relies on grouping samples based on their morphological features. Statistical approaches, such as the likelihood ratio method, play a crucial role in quantifying how much more likely observed data is to support one hypothesis over another. For example, Hook, Fieldhouse, Flatman-Fairs, and Williams (2024) reviewed ten classification techniques from 14 sources to systematically classify bloodstain patterns. Zou and Stern (2022) utilized a bivariate Gaussian model to estimate the feature distributions under particular hypotheses and applied the likelihood ratio to distinguish between impact and gunshot patterns. In subsequent research, Zou and Stern (2025) proposed a semi-projected normal distribution mixture model to describe bloodstain patterns. This model outperformed the semi-wrapped Gaussian model in clustering synthetic data, highlighting its potential for more accurate classification.

With emerging AI technologies, machine learning and deep learning can enhance classification accuracy, decrease human subjectivity in bloodstain analysis, and minimize computation time, all of which would allow for high-throughput analysis. For instance, Jung, Jo, Ahn, Jeong, and Lim (2024) explored the use of machine learning frameworks, such as Convolutional Neural Networks (CNNs), Decision Trees, and Random Forests, to classify bloodstain patterns. Their findings demonstrated that the CNN Inception v3 model could automatically classify drip stains and blood spatters, significantly accelerating investigative processes (Bergman et al., 2022). Similarly, Rough, Batchelor, Green, and Bainbridge-Smith (2024) employed computer vision techniques to detect bloodstains in digital images on plain backgrounds, underscoring the potential of automated approaches in forensic investigations. This automated bloodstain pattern analysis represents a valuable tool for analysts and researchers exploring quantitative methods. Furthermore, integrating blood pattern analysis with the 3D imaging and characterization techniques discussed in subsequent sections offers immense potential for on-site investigations. Such interdisciplinary efforts promise to enhance bloodstain analysis's accuracy, precision, and interpretability, further advancing its forensic applications.

Laboratory-Based Bloodstain Age Estimation.

After exiting the human body, blood undergoes a series of distinct physical and chemical transformations over time, driven by the degradation of DNA, RNA, proteins, and other biomolecules. These temporal changes are critical in forensic investigations, providing clues about the time since blood deposition. Initially, fresh blood appears bright red due to the presence of oxygenated hemoglobin (oxy-hemoglobin), which reflects red light. The oxidation of hemoglobin causes methemoglobin to develop over time, giving bloodstains a darker brown color. Eventually, hemoglobin is further degraded into hemichrome, contributing to a dark brown to black coloration. These changes are primarily driven by chemical reactions with oxygen in the air and the breakdown of hemoglobin derivatives.

Forensic scientists leverage these biochemical changes to approximate the time since blood deposition, a key factor in reconstructing timelines, identifying suspects, or ruling out individuals in violent crimes. Achieving precise measurements of bloodstain age in real-world scenarios is challenging due to the influence of numerous environmental variables, including light exposure, temperature, humidity, microbial activity, contamination, the kind of substrate the blood is deposited, and the bloodstain's thickness. These factors can accelerate or delay the degradation processes, introducing variability in the interpretation of results. Bloodstain age estimation has been the subject of significant research since 1907 (Das, Harshey, Nigam, Yadav, & Srivastava, 2020). Since the beginning of the last decade of the twentieth century, several researchers have been studying the effects of time on the aging of different pieces of evidence to ascertain the exact or relative time of their occurrence. Despite the importance of bloodstain age estimation, due to these complexities, no single method has been universally adopted for routine use in crime scene investigations.

Since 2020, forensic analyses of bloodstains have increasingly focused on molecular biology techniques, with DNA and RNA analysis at the forefront. DNA-based methods have been used to examine changes in specific sequences (He et al., 2022; Yang et al., 2023), while RNA-based approaches have explored messenger RNA (mRNA) and microRNA (miRNA) degradation as indicators of bloodstain age. For example, RNA degradation rates can ascertain the estimated period since deposition, as RNA is less stable than DNA and degrades at a predictable rate under specific conditions (Elliott, Stotesbury, & Shafer, 2022; Fang et al., 2020; Heneghan, Fu, Pritchard, Payton, & Allen, 2021; Manasatienkij & Nimnual, 2021; Wei, Wang, Wang, Cong, & Li, 2022).

Other biochemical techniques focus on studying hemoglobin and protein modifications. High-performance liquid chromatography (HPLC) has been used to measure levels of hemoglobin A1c, a form of hemoglobin that undergoes glycation, as a function of time (Acar et al., 2020). Liquid chromatography-tandem mass spectrometry (LC-MS/MS) has made it possible to identify specific protein modifications, such as oxidation, deamidation, and glycation, which provide valuable indicators for bloodstain age estimation (Heo et al., 2022; Kim et al., 2022; Lee, Lee, Kwon, Lee, & Kang, 2022; Schneider, Roschitzki, Grossmann, Kraemer, & Steuer, 2022; Schneider, Kraemer, & Steuer, 2023).

Morphological and mechanical changes in red blood cells over time have also been investigated using advanced imaging techniques. Atomic Force Microscopy (AFM) has been employed to monitor the elasticity and surface morphology of red blood cells as they age, revealing distinct degradation patterns (Cavalcanti & Silva, 2019; Strasser et al., 2007). Scanning Electrochemical Microscopy (SECM), a technique that maps the electrochemical activity of bloodstains, was employed by Tian, Chen, Ma, and Zhang (2022) to track changes in cell membranes and protein interactions over time.

While these laboratory-based methods provide high precision and detailed insights, they are often impractical for on-site forensic investigations. The reliance on sophisticated instruments, chemical reagents, and trained specialists makes these methods time-intensive and resource-heavy (Seki, Hsiao, Ishizawa, Sugano, &Takahashi, 2024). Furthermore, the need for controlled conditions in laboratory environments limits their applicability in real-world crime scenes. Mobile DNA labs have been developed since the 2010s to enable rapid on-site analysis, particularly in mass disaster scenarios. However, high equipment maintenance and operational costs remain significant drawbacks. Concerns also persist regarding their accuracy and the risk of contamination compared to traditional lab-based methods, raising questions about their scientific rigor and reliability for use in court. As a result, the field has seen a growing interest in portable spectroscopic and colorimetric techniques to close the gap between laboratory precision and practical usability in on-site investigations.

On-Site Bloodstain Age Estimation.

Modern spectroscopic and colorimetric techniques offer the capability to estimate bloodstain age with compact instrumentation (Figure 3). The absorption and reflection of electromagnetic waves at specific wavelengths by the hemoglobin derivatives provide the basis for spectroscopic and colorimetric analyses of bloodstains (Bremmer, Nadort, van Leeuwen, van Gemert, & Aalders, 2011; Bremmer, de Bruin, van Gemert, van Leeuwen, & Aalders, 2012). By measuring the spectral properties of bloodstains in the laboratory, researchers can estimate their age, as the progression of hemoglobin degradation follows a predictable timeline under controlled conditions. However, the practical application of such methods is often limited due to the variability introduced by external factors. Despite challenges posed by environmental factors, substrate variability, and measurement conditions (Zadora & Menżyk, 2018), substantial progress in on-site analysis has been made to mitigate these limitations.

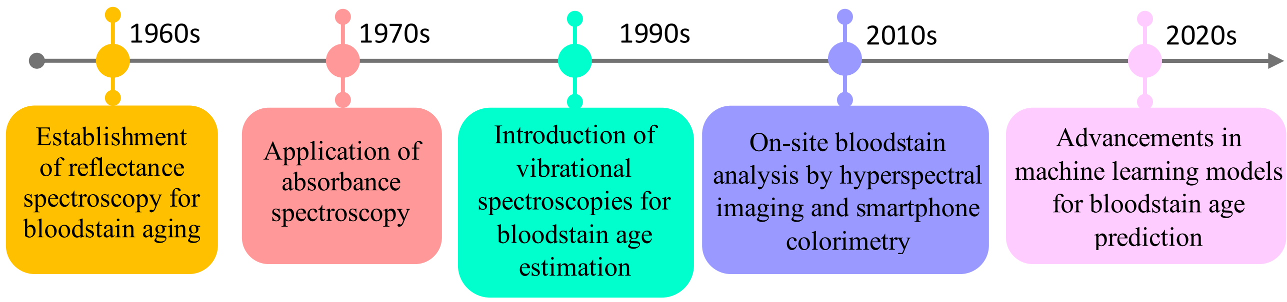

Figure 3. Evolution of on-site bloodstain age estimation (Authors' source).

Reflectance, Absorbance, and Fluorescence Spectroscopies.

In 1960, Patterson proposed that temporal changes in molecular and structural characteristics of the bloodstain can be detected in reflectance spectra and correlated with the bloodstain age (Patterson, 1960). Reflectance spectroscopy measures the sample's reflection of IR or visible light to gather information about its composition. By illuminating the sample's surface, the spectrometer collects the reflected light intensity in relation to wavelength, creating a reflectance spectrum. Alternatively, an early work by Kind, Patterson, and Owen (1972) suggested that the absorbance spectra could be used in estimating the age of bloodstains.

Subsequent studies in the 2010s sought to enhance the accuracy of these methods. To manage complex spectral datasets, chemometric methods, including partial least squares regression (PLSR) and principal component analysis (PCA), have been used in bloodstain analysis to derive valuable data and facilitate more accurate interpretations with statistical confidence (Sharma & Kumar, 2018). Bremmer et al. (2011; 2012) used reflectance spectroscopy to identify the hemoglobin derivatives and determine the age of blood stains. Li, Beveridge, O'Hare and Islam (2011) employed spectral pre-processing and linear discriminant analysis to develop a predictive model for age estimation up to 37 days based on spectral properties of equine blood on a glazed white tile. Sun et al. (2017) applied 3 chemometric methods to develop a prediction model for bloodstained aged 2–24 h, 1–7 days, and 7–45 days based on reflectance spectroscopy. The least-squares-support vector machines (LS-SVM) outperformed the PLSR and PCA.

Hanson and Ballantyne (2010) demonstrated the use of a Ultraviolet-visible (UV-vis) spectrophotometer to monitor the blue shift attributed to the modifications of hemoglobin and its derivatives in bloodstains aged up to 1 year. The effects of temperature and humidity were also investigated. Bergmann, Heinke and Labudde (2017) studied bloodstain ageing for up to 3 weeks on different substances and subsequently studied the effect of the coagulation agent from UV-vis absorbance spectra of bloodstains (Bergmann, Leberecht, & Labudde, 2021).

On the contrary, fluorescence spectroscopy measures the amount of fluorescent light that is emitted from a sample after it has been energized by a light source. As a result of photon absorption, a molecule can enter an excited state and subsequently emit fluorescence as it returns to its ground state. The technique, therefore, provides details regarding the molecule structure, energy levels, and chemical environment of the fluorescent molecules in the sample. In the context of bloodstain age estimation, fluorescence spectroscopy is employed to examine the temporal changes of fluorophores in blood, especially tryptophan. Weber, Wójtowicz, and Lednev (2021) found that the fluorescence intensity significantly decreases within 24 hours, and the emission spectra exhibit shifts in peak positions. To determine the age of bloodstains, mathematical models were created using the fluorescence data obtained from blood samples with known ages.

Vibrational Spectroscopy.

Since 1990s, Fourier Transform Infrared (FTIR) and Raman spectroscopies have been developed to provide more accurate and detailed analysis of bloodstains. Both spectra are derived from characteristic vibrational modes and frequencies within molecules. Because each sample has a unique set of molecular bond vibrations, these two vibrational spectroscopies can be complemented to characterize different functional groups (Das, Harshey, Nigam, Yadav, & Srivastava, 2020). The effects of interfering substances and substrates may also be discriminated (Kistenev, Borisov, Samarinova, Colón-Rodríguez, & Lednev, 2023; Sharma, Chophi, Jossan, & Singh, 2021). For FTIR spectroscopy, the frequency of absorbed IR light equal to the vibration frequency of the functional groups in bloodstains was identified, and PLSR was often used in the analysis. The linear correlation between FTIR parameters from characteristic vibration bands and the blood deposition time could be established and further developed for forensic investigation. Edelman, van Leeuwen, and Aalders (2012b) compared ageing bloodstains with non-blood controls on cotton fabrics of different colors. From the Near Infrared (NIR) spectra, the time since deposition up to 1 month was correctly predicted but the uncertainty was significantly increased after 10 days. The Attenuated Total Reflection Fourier Transform Infrared (ATR-FTIR) enhances the sensitivity in determining the functional groups by incorporating a reflective crystal in the set-up (Alkhuder, 2022). ATR-FTIR with PLSR was used to compare indoor and outdoor bloodstains ranging in age from 1 to 85 days (Lin et al., 2017). From ATR-FTIR spectroscopy coupled with chemometric techniques, Kumar, Sharma, and Sharma (2020) obtained the estimation model for up to 175 days.

In Raman spectroscopy, photons are inelastically scattered by molecules in a sample. When a laser beam is directed at a bloodstain, the interaction between photons and the molecules found in the sample causes a shift in the energy levels of the photons, resulting in scattered light with different wavelengths. This scattered light contains information on the molecular composition and structure of the sample. Raman spectroscopy is at the forefront of research and allows for single-point observations. However, its practical application is currently limited by several factors, including the high cost of equipment, variability in results depending on the substrate, and the need for specialized expertise to ensure consistent and reliable measurements (Doty, McLaughlin, & Lednev, 2016; Seki, Hsiao, Ishizawa, Sugano, & Takahashi, 2024). In the context of bloodstain age estimation, Raman spectroscopy analyzes the changes in the molecular components of blood over time. As blood ages, the transformation of hemoglobin molecules alters their Raman spectra. By comparing the Raman spectra of bloodstains with known ages to those of unknown stains, the age of the bloodstains can be estimated based on the degree of spectral similarity or dissimilarity. Various Raman spectroscopic parameters, such as the intensity ratios of specific Raman bands or the presence of characteristic peaks, have been explored to develop models for estimating bloodstain age. These models are typically created using multivariate analysis or machine learning algorithms to correlate the Raman spectral data with the known ages of bloodstains. Doty, McLaughlin, and Lednev (2016) used PLSR calibration curves to predict the bloodstains aged up to 1 week and, in a subsequent work, estimated the bloodstain age of up to 2 years based on Raman spectra (Doty, Muro, & Lednev, 2017). More recently, datasets from Raman spectra of bloodstains under varying temperatures and humidity levels were used to build prediction models using Support Vector Machine Regression (SVR), Kernel Ridge Regression (KRR), and CNN (Zhang, Wang, Chen, Tian, & Gao, 2023).

Colorimetry.

Fresh bloodstains typically exhibit a bright red color, while older stains appear darker and brownish. This color change is attributed to iron oxidation and hemoglobin breakdown after leaving the blood vessel. Accurately determining the time since deposition based solely on color remains challenging due to its sensitivity to aforementioned environmental factors and lighting conditions during measurement. However, significant progress in estimating bloodstain age based on color has been achieved over the past decade. For instance, Thanakiatkrai, Yaodam, and Kitpipit (2013) captured digital images of bloodstains under controlled lighting conditions using a light box and analyzed the images with the ImageJ program on a personal computer. They examined time-dependent colorimetric characteristics in CMYK, HSV, HSL, and RGB color spaces and recommended monitoring the M value, which exhibits a logarithmic decrease over time with the highest R^2 for estimating bloodstain age. Several parameters, including anticoagulants, humidity, light exposure, temperature, and substrate type, which significantly affect the rate of color change in bloodstains, were also explored in this study (Thanakiatkrai, Yaodam, & Kitpipit, 2013).

A spectrophotometric colorimeter can measure the transmittance and reflectance of the continuous spectrum to determine the color tone, enabling the explicit estimation of bloodstain color changes over time (Seki, Hsiao, Ishizawa, Sugano, & Takahashi, 2024). In the 1950s, when spectrophotometry was the primary method of study, obtaining the reflectance spectrum of the visible light region took almost an hour, making the process time-consuming (van Kampen & Zijlstra, 1961). Despite its simplicity and relatively low cost (Kind, Patterson, & Owen, 1972), spectrophotometry holds high accuracy potential but faces reproducibility challenges, particularly due to its reliance on broad spectra within the visible light range (Sun et al., 2017). Marrone et al. (2021) employed a spectrophotometric colorimeter to capture CIELAB/CIELCh color values over time as blood transitioned from bright red to dark brown. By correlating these color values with bloodstain aging, they developed predictive models to estimate the time since deposition. With advancing AI technology, Seki, Hsiao, Ishizawa, Sugano, and Takahashi (2024) applied machine learning techniques to estimate bloodstain age by analyzing time-dependent color changes using a spectrophotometric colorimeter. They quantified the color tone of each bloodstain in the CIELAB color space and developed a predictive model for bloodstain age using a random forest regression approach.

The emerging field of smartphone colorimetry harnesses the power of both smartphone cameras and colorimetric applications (apps) to quantify colors. The "Smart Forensic Phone," an Android-based smartphone app developed by researchers at Yonsei University, was a significant advancement in crime scene analysis (Shin et al., 2017). This app utilized colorimetric analysis in the HSV color space of the V value to rapidly determine the time since blood deposition on five different substrates. However, it should be noted that the colorimetry approach may not be as effective beyond 42 hours, as bloodstain colors tend to exhibit minimal changes after this time. Furthermore, the Yonsei research group has expanded their work by incorporating classification and pattern recognition capabilities for cracks and blood pools in smartphone images to determine bloodstain age while still relying on the V value from the colorimetric study (Choi, Shin, Hyun, Song, & Jung, 2019). Dinmeung, Sirisathitkul, and Sirisathitkul (2023) used the iPhone application called "Colorimeter X" to analyze the bloodstains left on tissue papers and cotton fabrics over one to eleven days, corresponding to the CMYK, HSV, and RGB color schemes. They observed linear decreases in R, G, B, and V values as the temporal transitions from bright red to dark brown. The V value has the highest R2 based on linear least square fitting. The increase in the K value during the blood aging process was identified as an additional effective metric to support the B, R, and V values in estimating the bloodstain age. Besides the colorimetry, Li et al. (2023) demonstrated that images of bloodstains could be analyzed by deep learning-based BloodNet and correlated their pattern to the time since deposition.

Hyperspectral Imaging.

Since 2012, hyperspectral imaging has been utilized to assess the age of bloodstains, offering a cutting-edge approach to forensic analysis. This technique captures images across multiple electromagnetic spectrum wavelengths, typically spanning visible and nearinfrared regions, using advanced portable devices. The resulting data, known as a hypercube, gives a spectrum for each pixel (x, y) and an image for each wavelength, enabling detailed characterization of the reflectance or absorption of various substances within the samples (de Cassia Mariotti, Ortiz, & Ferrao, 2023). Edelman, van Leeuwen, and Aalders (2012b) correlated the spectral characteristics with the relative amount of hemichrome, methemoglobin, and oxyhemoglobin in bloodstains, leading to a non-destructive approach for estimating age up to 200 days. Li, Beveridge, O'Hare, and Islam (2013) investigated spectral variations in bloodstains over time and developed a model for estimating age up to 30 days based on the collected hyperspectral images and linear discriminant analysis. Their model was particularly accurate within the first 7 days but had a higher error rate, particularly after 14 days. Cadd, Li, Beveridge, O'Hare, and Islam (2018) focused on the bloodstained fingerprints and observed the variation in visible light absorption by hemoglobin derivatives with bloodstain age. With Forenscope-Mobile Multispectral UV-VIS-IR Imaging Systems, Kaya, Karadayi, Karadayi, and Çetin (2023) studied bloodstains of varying ages on textiles under various washing circumstances. Giulietti, Discepolo, Castellini, and Martarelli (2023) utilized hyperspectral images of bloodstains deposited on nine different substrates, varying in color and composition, to estimate the age of bloodstains using a multilayer perceptron regression model. Unlike other methods based on hemoglobin kinetics, this approach overcomes the limitations posed by environmental factors such as temperature, humidity, and others.

Conclusions and Outlook.

Since its inception, the forensic science of bloodstain analysis has undergone significant evolution, with its roots tracing back to early visual approximations of bloodstain characteristics. The pattern of bloodstains has always been crucial in forensic investigations. Moreover, blood pattern analysis provides valuable insights into the mechanics of bloodshed at crime locations. By examining the size, shape, and distribution of bloodstains, investigators can infer key details, including the angle of impact, the velocity of blood spatter, and the nature of the force involved. Historical advancements in this field, from early qualitative assessments to modern computational modeling, have transformed it into a powerful tool for reconstructing events.

Over time, advancements in technology have expanded the scope of bloodstain analysis to include age estimation alongside blood pattern analysis, providing critical insights into the timing of criminal events. In its earliest days, investigators relied on simple observations of color changes in drying bloodstains, which could only offer rudimentary estimations. Integrating spectroscopy and colorimetric techniques has significantly improved the accuracy and applicability of bloodstain age estimation. Raman Scattering and FTIR spectroscopy have emerged as non-destructive methods for characterizing molecular vibrations in blood components, allowing for detailed assessments of chemical changes that occur as bloodstains age. Similarly, UV-visible spectroscopies, including reflectance, absorbance, and fluorescence, exploit the interaction of light with blood to extract valuable information about hemoglobin degradation and other biochemical markers over time. These advancements in optical methods have moved forensic science closer to reliable, on-site applications for age determination.

Alongside spectroscopy, hyperspectral imaging has proven particularly promising by combining imaging with spectral analysis to comprehensively assess bloodstains across a wide range of wavelengths. This approach not only aids in age estimation but can also offer spatial context for interpreting bloodstain patterns, bridging the gap between quantitative analysis and visual interpretation. Additionally, smartphone-based colorimetry has emerged as a cost-effective and portable alternative, enabling investigators to track colorimetric changes in bloodstains over time with high precision. However, environmental factors such as temperature, humidity, substrates, and stain thickness remain challenges, potentially influencing the accuracy of these methods.

Integrating AI technologies into bloodstain pattern analysis and age estimation represents a transformative advancement in forensic science, offering a more precise, objective, and high-throughput approach to interpreting bloodstains. Machine learning and deep learning frameworks, such as CNNs, decision trees, random forests, support vector machines, and multilayer perceptron models, have demonstrated remarkable potential in classifying bloodstain patterns, estimating bloodstain age, and minimizing the impact of environmental variables. The combination of spectroscopy, hyperspectral imaging, and colorimetric analysis with AI-assisted predictive modeling is enhancing the accuracy and applicability of bloodstain analysis across forensic investigations.

Despite these advancements, several challenges remain. The lack of standardized protocols and the influence of external factors such as temperature, humidity, and substrate properties continue to affect model generalizability. Future research must prioritize the expansion of large-scale, high-quality datasets encompassing a wider range of conditions to improve model robustness. The development of more adaptive and interpretable AI models, capable of integrating multimodal data sources, including spectral, colorimetric, and spatial pattern information, could significantly enhance forensic reliability.

Moreover, interdisciplinary collaboration between forensic scientists, AI researchers, and law enforcement agencies will be critical in translating these AI-driven methodologies into practical forensic applications. Efforts to validate AI models through repeated experiments, cross-laboratory testing, and calibration refinements will be essential to ensure their credibility in judicial proceedings. Additionally, the integration of automated 3D imaging, real-time computer vision systems, and explainable AI could further refine the forensic workflow, making on-site bloodstain analysis more accessible and interpretable for investigators. By addressing these challenges, the integration of AI in forensic bloodstain analysis will continue to push the boundaries of forensic science, enabling more reliable, rapid, and scientifically rigorous bloodstain interpretation that withstands scrutiny in legal contexts.

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Conflicts of interest.
The authors declare no conflict of interest.

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Плями крові в судово-медичній експертизі: Від візуального огляду до аналізу зразків та оцінки часу за допомогою ШІ

Анотація. *Кров'яні плями давно служать важливим доказом у судово-медичних розслідуваннях, надаючи відомості про час та природу насильницьких злочинів. У статті прослідковується історичний розвиток аналізу кров'яних плям, від початкової візуальної інспекції до впровадження сучасних методів та технологій. Аналіз кров'яних плям тепер став системною наукою і інтегрував технології штучного інтелекту, надаючи кількісні відомості про механізми розбризкування крові. Для оцінки часу кров'яних плям використовується аналіз ДНК, який дозволяє виявити тимчасові зміни в генетичних матеріалах із деградованих плям крові. Високопродуктивна рідинна хроматографія доповнила дослідження кров'яних плям, кількісно визначаючи біохімічні маркери, що вказують на час з моменту їх відкладення. Спектроскопічні методи, зокрема раманівська та інфрачервона спектроскопія, виявили специфічні молекулярні вібрації, пов'язані з тимчасовою деградацією компонентів крові, тоді як оптичні методи на основі відбиття фотонів, абсорбції та флуоресценції пропонують альтернативні шляхи для оцінки віку кров'яних плям. Колориметрія на базі смартфонів стала економічно ефективним і портативним рішенням, відстежуючи видиму зміну кольору крові від яскраво червоного до темно-коричневого з часом. Більше того, гіперспектральна візуалізація поєднує візуалізацію і спектроскопію, дозволяючи оцінювати вік з просторовою роздільною здатністю, аналізуючи спектральні дані на рівні пікселів. У статті підкреслюється історичний розвиток та технологічні досягнення, які сформували аналіз кров'яних плям у судово-медичній дисципліні. Інтегруючи сучасне обладнання з технологіями ШІ, ця галузь наближається до надійного аналізу на місці. Проте існують проблеми, такі як варіативність середовища, вплив субстратів та стандартизація. Продовження досліджень та валідація є необхідними для вдосконалення цих методів і встановлення стандартизованих протоколів для судових застосувань. Цей історичний та технічний огляд підкреслює трансформуючий вплив міждисциплінарних інновацій на розвиток аналізу кров'яних плям, що поєднує дослідження в лабораторії та практичне застосування в судово-медичних умовах.*

Ключові слова: *аналіз плям крові; оцінка часу; спектроскопія; гіперспектральна візуалізація; колориметрія на смартфоні*

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Comparative analysis of medieval Georgian and European medical treatises and remedies

Abstract. *The practice of medicine in Georgia has its roots in antiquity and is deeply intertwined with the medical traditions of ancient Greece and Rome. This rich scientific heritage is clearly reflected in early medieval Georgian medical traditions. In medieval Georgian historical writings contain specialized medical texts and treatises, demonstrating the advanced state of medical knowledge at the time. Among these texts, the 11th-century Georgian medical text Ustsoro Karabadini ("Incomparable Medical Handbook") holds particular significance as an original Georgian medical treatise incorporating not only Georgian medical expertise but also insights from both ancient and medieval European medical traditions. The parallels between this text and Western European medical treatises are apparent from the very beginning. The text incorporates the Hippocratic and Galenic concept of the four humors, outlining the ailments linked to each humor and their respective treatments. Additionally, Ustsoro Karabadini offers health recommendations based on seasonal* *changes, describing the challenges the human body faces throughout the year and providing guidance on overcoming illness and maintaining proper nutrition. The treatise also includes noteworthy insights into pregnancy, gender prediction, and childcare practices. It places particular emphasis on a balanced diet, detailing the appropriate consumption of plant- and animal-based foods. A notable section is dedicated to the medicinal benefits of wine, a subject deeply ingrained in both Georgian and European traditions, where it was closely associated with daily life and sacred significance of Christian rituals. The analysis of these treatises clearly demonstrates that, similar to Europe, Georgia developed agricultural practices, particularly the cultivation of vines and cereals. Historical and archaeological research confirms that the tradition of cultivating grapevines and wheat in the Caucasus region dates back to the Neolithic era. The Georgian territory is considered one of the oldest centers of viticulture and wheat cultivation. An analysis of medical treatises reveals that prolonged engagement with these agricultural practices both in the Georgian and broader European contexts contributed to the discovery of similar medicinal properties associated with these crops. A comparative analysis of Ustsoro Karabadini and European medical treatises suggests that Georgian medicine was significantly influenced by both European and ancient (Greek-Roman) medical traditions, sharing many common characteristics with them.*

***Keywords**: Middle Ages; medical book; Georgia; medical treatises; Ustsoro Karabadini*

Introduction.

The history of medicine is divided into different periods with modern approaches linking its achievements to different civilizations or historical epochs. Western medicine, reflecting the dominance of Western civilization, originates from European history. However, it is widely accepted that medical progress is the result of collective efforts by different nations (Kashif, 2008, p. 154). Like other scientific fields, medicine underwent a complex and fascinating stage of development during the Middle Ages.

The daily life of medieval individuals and society as a whole was filled with dangerous challenges and threats. Coping with wounds, injuries, epidemics, and infections was a crucial aspect of everyday existence. The medical field of this period encompassed diverse elements, including traditional healing methods, incantations, magic, relics of saints, and even the phenomenon of the "royal touch" (Alford, 1979, p. 380). Despite these mystical aspects, medieval medical treatises preserved a wealth of essential knowledge that contributed to the foundation of modern medicine. These treatises contained extensive information on the nature and symptoms of diseases, often incorporating elements of magical beliefs (Luscombe, 2008, p. 484). They exemplified the synthesis of classical medical knowledge with local folk practices and traditional belief systems. (McVaugh, 1997, p. 55). The works of Hippocrates (c. 450–370 BCE) and Galen of Pergamon (129–200 CE) became the cornerstone of medical traditions for Mediterranean civilizations (Conrad, Neve, Nuton, Porter, & Wear, 1995). In addition to ancient traditions[1], medieval medical treatises from various European regions included extensive knowledge on the medicinal applications of plants, animals, and minerals specific to certain ethno-geographical environments (Stannard, 2013, p. 47). Comparable medical theories are documented in early and high medieval European treatises, such as Isidore of Seville's Isidori Etymoligiarum Sive Originum Liber IV: de Medicina, the 6th-century treatise "On the Wisdom of the Art of Medicine" (Sapientia Artis Medicinae), the 11th–12th-century Salerno medical treatise (Regimen Sanitatis Salernitanum), as well as in the recommendations of prominent 13th–14th century Italian and Spanish physicians.

During the early Middle Ages, medicine was deeply intertwined with religious doctrines and magical beliefs. However, beginning in the 11th century, it gradually developed into a distinct scientific discipline, experiencing a revival unparalleled since the time of Galen (Cumston, 1926, p. 212). This period is considered a turning point when classical medical traditions were consolidated into treatises and integrated into university curricula. Simultaneously, folk healing methods and elements of magic began to fade into the background (McVaugh, 1997, p. 54).

From the 11th century onward, the study of ancient medical heritage became more active, with significant influence from the works of Islamic scholars. Karabadini texts gained widespread popularity and were also disseminated in Europe. These works played a crucial role in the advancement of medicine, serving as a bridge between Western and Eastern cultural heritage (Abuladze, 2010, p. 11). In Georgian medical science, it is widely accepted that knowledge from the classical Greco-Roman period was transmitted primarily through the Eastern Arab-Persian route, with Byzantine influences also playing a role to some extent. In turn, the Arab-Persian medical tradition was profoundly shaped by this classical heritage.

In the Middle Ages, the medical system, which included monastic professional medicine and folk medicine, also covered family-line and military medicine, bringing together practitioners of various statuses. This system united "skilled" professional doctors, "healers of the soul and body, physicians", folk healers, and military physicians. It was not uncommon for one individual to serve as both a healer of the soul and body or to hold roles as a military doctor and a practitioner of family-line medicine. (Mindadze, Antadze, & Chelidze, 2023).

In Georgia, which was once part of the ancient and Hellenistic worlds and later became a crossroads between Eastern and Western civilizations, early accounts of

[1]Ancient authors such as Dioscorides (1st century AD) in his "De Materia Medica", Pliny the Elder (AD 23–79) in "Naturalis Historia", and Claudius Claudianus (4th–5th centuries AD) in "In Rufinum" noted the rich diversity of medicinal herbs found in Georgia, specifically in the region historically known as Colchis. They observed that identical or similar herbs were also present in regions such as Galatia and Messina, where these herbs were similarly employed for therapeutic purposes. Claudianus further remarked that the mythical figures Medea and Circe gathered various medicinal and toxic herbs in the mountainous areas of the Caucasus and Scythia (Caucasus Antiquus. Encyclios Disciplina, 2010, p. 311; p. 593; p. 687).

medical practices and diseases can be found, even during the early spread of Christianity.[2]

It is noteworthy that in the 10th century, considered a pivotal era for the development of medicine in Europe, a Georgian medical treatise known as Ustsoro[3] Karabadini was created (Kanaanite, 1940). While it is not the only medical treatise[4] produced in medieval Georgia, it is distinguished by being an original work, rather than a direct translation, and is recognized as the oldest surviving Georgian medical text (Shengelia, 1980). Information about the evolution of medieval medicine can also be found in Georgian sources.

It is known that King David IV the Builder[5] "established a xenon[6] in a suitable and beautiful location, where he gathered individuals (brothers) suffering from various ailments and provided them with all necessary care" (Kaukhchishvili, 1955, p. 331). Similar to European traditions, Georgian medical practices were strongly influenced by religious institutions. Numerous medical and cultural centers, along with hospitals, were established both within Georgia and beyond its borders, including at the Iviron Monastery on Mount Athos, the Georgian Lavra of Sabatsminda, the Gelati Monastery, and the ecclesiastical-cultural centers of Tao-Klarjeti (Shengelia, 1980, p. 100). Moreover, Georgian medical treatises reflect a fusion of both Western and Eastern medical traditions, shaped by the region's unique geographical position (Shengelia, 1999).

Medieval Georgian literature also contains medical texts that address topics in physiology and anatomy. These works include both original compositions and translated exegetical or apocryphal writings. Notable examples include at the "Creation of Man" translated by Giorgi Mtatsmindeli (11th century) and "On the Nature of Man" translated by Ioane Petritsi (11th century).

Additionally, it is worth mentioning that Chapter XXX of the significant 10th-century Georgian manuscript, the Shatberdi Codex (copied at the Shatberdi Monastery), titled The Creation of Man, is a translation of a Greek treatise. Also, various works by Georgian translators, editors, and philosophers.

The medical treatise mentioned above is quite voluminous and contains a wealth of interesting information. "Ustsoro Karabadini" follows the traditional approach

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[2] The hagiographic work "The Life of Saint Nino" by Leonti Mroveli, the author of "The Life of Kartli", contains references to these issues. According to him, folk healers existed in the Kingdom of Kartli during this period (Mindadze, Antadze, & Chelidze, 2023).

[3] Ustsoro (Georgian: უსწორო) – Incomparable, flawless. There are differing views in historiography regarding the time of the creation of this work. Some believe it was written in the 10th century, although its creation dates do not go beyond the 10th-11th centuries (Kuchianidze, 1997. P. 51-52).

[4] It should be noted that "Tsigni Saakimoi" (the Book of Medicine) was created in the first half of the 13th century (1206). However, this treatise represents a translation of Eastern medical traditions. The book entered Georgia during the reign of Queen Tamar (1184-1210), following a battle between the Georgians and the army of Sultan Rukn ad-Din of Rum. Along with the vast spoils of war, the Georgians acquired this medical treatise, which had been translated from Arabic into Georgian by the former Khoja (Kotetishvili, 1936, p. XXIII-XXVI; Shengelia, 1980, p. 5; Samushia, 2023, p. 78).

[5] David IV Bagrationi, King of Georgia 1089-1125.

[6] Xenon is a Greek word: in ancient times in Georgia, it was the name for a place where patients were received, a hospital.

typical of manuscripts of this kind. It consists of three main sections and is divided into chapters (Heads, Georgian: თავი). These include a general philosophical description of medicine, medical advice, and then a list of diseases and their treatment methods, medical principles, anatomical, physiological, and pharmacological concepts, specific pathology and therapy, general gynecology, skin diseases, treatment methods for fractures, burns, and bites. It also covers hygienic and dietary concepts, as well as descriptions of medicines (Kanaanite,[7] 1940, pp. XI–XVIII; Kuchianidze, 1997, pp. 46–50).

The goal of this article is to identify parallels between the treatment methods outlined in the 11th-century Georgian medical treatise and those found in medieval European medical texts, as well as to examine the medicinal properties or potential harmful effects of various plants and food products. Based on these similarities, we aim to compare and analyze Georgian and European medical traditions. Furthermore, our research seeks to explore the extent to which Western medical knowledge, alongside Eastern influences, was incorporated into Georgian practice, and whether both traditions, by nature, followed similar approaches to treatment.

Research Methods.

The methodology of our research is primarily grounded in source study, which has determined the use of both general scientific and specialized research methods. Analyzing medical treatises allowed us to apply various historical research approaches. Since the basis of the study was the selection of the original Georgian source, we attempted to compare it with corresponding European sources. Throughout the research process, we utilized methods of comparative and critical analysis of the sources.

In the European academic context, the history of medicine has long been a subject of extensive and multifaceted scientific research. In contrast, research into the history of Georgian traditional medicine has developed mainly during the second half of the 20th century. This research encompasses both the study of Georgian medical treatises and the analysis of rich medical knowledge embedded in Georgian ethnological traditions.

Significant contributions to the field have been made by scholars such as M. Shengelia, L. Kotetishvili and N. Mindadze, whose works have significantly deepened our understanding of the history of Georgian medicine. Medieval Georgian medical treatises contain a wide range of information and have significant potential for interdisciplinary study.

[7] The author of this book is some person from Kanaan - Kanaanite, whose identity and origin remain unknown. On the margin of page 36 of the text, there is an inscription where the writer asks for God's forgiveness: “Whoever reads this, may God command forgiveness for the Kanaanite”. Therefore, the author is referred to as “Kanaanite” in historiography. Scholars believe that he is Georgian. The references in the Karabadini reflect the Georgian reality of the time, which is confirmed by his extensive knowledge of the Georgian language, terminology, and customs. Although the Karabadini is heavily influenced by Byzantine and Arab medical knowledge, it also incorporates a significant amount of Georgian medical tradition in its texts (Kanaanite, 1940, pp. VIII-IX) (Samushia, 2023, pp. 34-35).

The subject of our research introduces a new perspective both in the Georgian and wider European scientific space. The originality of our research lies in its focus on a specific Georgian medical treatise and its deliberate goal: to identify parallels with modern European medical practices and to analyze the underlying reasons for these similarities.

Results and Discussion.

During the study of this issue, it became evident that identifying and highlighting the similarities between Georgian and Western healing traditions was essential. One similarity, which is immediately noticeable in both the Ustsoro Karabadini and Western European works, is the theory of the four humors[8] proposed by Hippocrates and Galen. According to this theory, the healthy human body is composed of a balance of four fluids: blood, phlegm, yellow bile, and black bile (Jouanna, 2012, p. 335). Disease was considered as the disruption of this balance of humors (Boylan, 2007, p. 212; Mendelsohn, 2013, p. 69).

It is stated in the Georgian medical treatise "…we have observed the signs and qualities of all four substances: blood, yellow bile, black bile, and phlegm" (Kanaanite, 1940, p. 8). Following this, the signs of diseases caused by each of these fluids and ways to address them are described. The information on the theory of the four humors is preserved in numerous written works from the early Middle Ages. Notably, a passage from Isidore of Seville (560–636) stands out (Isidori Etymologiarum Sive Originum Liber IV: de Medicina) (Sharpe, 1964, pp. 55–56), as well as the treatise Sapientia Artis Medicinae (Wisdom of the Art of Medicine) from the 6th century (Wlaschky, 1928, pp. 104–105). The most detailed similarity, however, is found in the 11th–12th century Salernitan medical treatise Regimen Sanitatis Salernitanum (The School of Salernum, n.d., pp. 115–121). The identity of these sections is an excellent illustration that, just like in European treatises, the Georgian medical work firmly reflects Greek and Roman healing traditions[9].

To contextualize these findings, we should examine the European analogs of the general therapeutic recommendations outlined in the Georgian medical treatise. Although the *Karabadini* is extensive, notable parallels can be identified in several

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[8] Theory of the four humors.

[9] How did antique medical knowledge likely enter Georgia? It is presumed that Arab rule and the growing Arab community in Tbilisi had a significant impact on all aspects of Georgian society. One example of this influence is the famous 12th-century Tbilisi-based Arab scholar Abu al-Fadl Hubaysh al-Tiflisi (Japaridze, 2012, pp. 61–68). He wrote numerous works on philosophy, medicine, astronomy, and other fields. Of particular note is his Kitab al-Adwiya ("The Handbook of Remedies"), written in Arabic in the 1030s. It consists of tables listing medicinal substances' names, preserved in Persian, Greek, Latin, and Syriac. It is likely that the knowledge of this Tbilisi-based Arab scholar influenced Georgian medical treatises. In Georgian medical scholarship, it is widely accepted that antique knowledge spread through the Eastern Arabic/Persian route. The Arab-Persian medical tradition itself was profoundly influenced by ancient classical heritage. A clear example of this is the work of one of the most influential Arab physicians of the 10th century, Ibn al-Jazzar. His works were extensively used in medieval European and Jewish medical education, and his writings were considered a mandatory part of the European medical curriculum (Makaryan & Avetisyan, 2023, p. 223).

European medical texts, as evidenced by their shared discussions of general therapeutic principles.

"Ustsoro Karabadini" provides information on the changing of the seasons and the challenges that arise for the human body as a result. According to the Georgian source: "In March, April, and May, the blood boils [...] the mood is hot and moist, and similarly, during these three months, the mood is hot and moist, and the blood boils [...] the hands should be opened" (Kanaanite, 1940, p. 26).

According to Sapientia Artis Medicinae, "From March onwards, there is an increase in all bodily fluids, especially blood. This causes irritation and swelling in both the body and mind. To alleviate this unhealthy state, bloodletting from the vein is recommended" (Wallis, 2010).

The medical treatise known as Regimen Sanitatis Salernitanum also mentions that: "In spring, the blood boils twice as much (is more active) as in other seasons, in the spring, open the vein and let the blood out" (Harington, 1953, p. 90).

In this case, all three medical treatises highlight that, during spring, blood becomes the most active of the four bodily fluids, leading to various challenges for the human body. To address this issue, all sources recommend bloodletting as the solution. This practice, widely used in ancient Egypt, Greece, and Rome, continued to be a common treatment throughout the Middle Ages (DePalma, Hayes, & Zacharski, 2007, p. 132).

Similar advice appears in both the Georgian source and European medical treatises regarding sleep: According to The Ustsoro Karabadini, "A long sleep […] harms a person, weakens his strength, burdens his head, and adds to the disease. […] Sleep should be taken in such a way that first lie on the right side, then on the left, for the parts of body alignment. Lying on the back makes the body rest well, but all the illnesses from the stomach will settle on the back" (Kanaanite, 1940, pp. 418–419). The harmful effects of long sleep are also discussed in the aforementioned Salernitan treatise. According to Regimen Sanitatis Salernitanum, "Long sleep will burden the head, weaken the body, and add moisture" (Thorpy, 2011, p. 24). As for recommendations regarding the proper sleeping positions, a similar analogy can be found in a letter by the Valencian physician Pedro Pagarola, written in 1315 to his two sons. The Spanish physician advised his sons: "Except in rare cases, avoid sleeping on the back, as it can cause many problems. Sleep on your side or on belly. First lie on the right side, then on the left (Thorndike, 1931, pp. 17–18)".

The Georgian treatise offers an interesting observation and method for determining the sex of an unborn child during pregnancy. According to the Ustsoro Karabadini: "If the right foot steps forward first while walking, it indicates a boy, and if the left foot steps forward first, it indicates a girl. If the right breast is clear and cheerful, and lightly swollen, it indicates a boy" (Kanaanite, 1940, p. 158).

While not entirely identical, a similar idea is found in several European treatises. A noteworthy example comes from the text of the 11th-century Italian physician, Constantine the African (also known as Monte Cassino). According to Constantine the African: "If the man's right testicle is larger, the offspring will be male, whereas if the left testicle is larger, the offspring will be female. […] If the sperm reaches the left side of the uterus, a female will be born; if it reaches the right side, a male will be born. […] The organs on the right side of the body produce male progeny, while those on the left side produce female progeny" (Delany, 1969, pp. 58–59).

In the section on newborn care, the Georgian source emphasizes the selection of a wet nurse, detailing the specific criteria that the caregiver should meet. According to the Ustsoro Karabadini: "The wet nurse should be of good character, not old, [...] she should be intelligent, not heavy when walking, should not be unnecessarily pained, so that there is no hidden cause inside her body, neither fat nor thin, [...] should not eat harmful or spicy food, otherwise, her milk will be deficient" (Kanaanite, 1940, pp. 158–159).

Similar criteria for choosing a wet nurse are emphasized by the 13th-century Italian physician Aldobrandino of Siena. In his medical treatise Régime du Corps, he developed the idea that "When selecting a wet nurse, her age, body shape, character, and condition of her breasts must be considered. She should be 25 years old, neither very thin nor very fat, but most importantly, she should be healthy. [...] She should be intelligent, not sad, foolish, or shy. [...] She should not eat onions, wild mustard, garlic, mint, or other strong-tasting foods that would spoil the milk" (Landouzy, Pépin, & Thomas, 1911, pp. 76–77).

Similar parallels can be found in treatments for dog bites, particularly in dealing with bites from rabid dogs. According to the Ustsoro Karabadini, when a person is certain that the dog was rabid, it recommends the use of several products in treatment: "Apply honey on top, [...] two onions [...] mix with a bit of melted butter and apply it" (Kanaanite, 1940, p. 413)

The same substances and food products are suggested for treating victims of rabid dog bites in the X Anglo-Saxon medical treatise, known as Bald's Leechbook (also Medicinale Anglicum) (Getz, 1998; p. 48; Kesling, 2020). According to the Old English text: "For a rabid dog bite, first apply a mixture of agrimony and honey [...] Take onion, fry it, and mix with butter [...] Apply it to the wound to expel the poison" (Cockayne, 1865, p. 145).

In both Georgian and European treatises, plant-based and animal-based substances are presented as methods of treatment. There are cases where the incompatibility and harm of certain foods or drinks are discussed. Additionally, there are given recommendations to avoid the simultaneous consumption of two products. The author of the Ustsoro Karabadini states that: "If you eat cheese, it is not right to eat fish. [...] It is heavier than fish and will disturb the heart" (Kanaanite, 1940, p. 433). This incompatibility between the two foods is also noted in the previously mentioned Salernitan treatise: "If you eat eel and cheese on the same day, it will disturb your stomach and heart" (The School of Salernum; Regimen Sanitatis Salernitanum, n.d., p. 37). Additionally, the Valencian physician in his letter to his sons warns against combining fish and dairy products: "Beware of consuming dairy products and fish on the same day, as it leads to leprosy and other ailments" (Thorndike, 1931, p. 17; Wallis, 2010, p. 503).

It should also be noted that the Ustsoro Karabadini and the letter from Valencian physician Pedro Pagarola both share the same attitude on avoiding the combination of milk and wine. The Ustsoro Karabadini advises: "If a person drinks milk and does not eat anything else he should not drink wine, until it digests and goes out" (Kanaanite, 1940, p. 433). "Beware of consuming milk and wine at the same meal, as the mixture causes indigestion and other misfortunes" (Thorndike, 1931, p. 17; Wallis, 2010, p. 503).

Extensive references to wine can be found in both Georgian and European treatises, as it was not only a common daily beverage but also held sacred significance in Christian society. According to the Ustsoro Karabadini, moderate wine consumption promotes bodily health: "A man who drinks wine in moderation preserves his health and avoids drunkenness". (Kanaanite, 1940, p. 457; Kuchianidze, 1997. pp. 123–124). A similar assessment of wine's effect on the human body is provided by Aldobrandino of Siena: "If wine is consumed in moderation, it will calm the person's mood, strengthen the body, and slow down aging" (Landouzy, Pépin, & Thomas, 1911, pp. 19–20; Jones, 1984, p. 107).

In the "Ustsoro Karabadini", there is also a discussion of the problems caused by excessive consumption of wine. From many examples, we can highlight one: "Wine can cause illness, as it can lead to a swelling of the throat" (Kanaanite, 1940, p. 458). Excessive consumption of wine is also mentioned as the cause of swelling in various organs in the Salerno treatise: "Wine, when consumed properly, is a good liquid; however, if consumed improperly, it may cause tumor wherever it reaches" (Harington, 1920, p. 30). However, wine is still considered a beneficial drink, as Karabadini suggests that if a sick person craves wine, it is a sign of recovery (Kanaanite, 1940, p. 15).

In general, the medicinal properties of wine are described in detail in Karabadini. The author also provides recommendations on which type of wine - white or red - is beneficial to consume during certain seasons. At the same time, the author gives suggestions on which wine pairs well with different foods. Additionally, the author warns against the excessive consumption of wine, not only due to its effects on health but for its potential harmful effects. At the same time, wine infused with water, known for its medicinal properties, is highlighted as a remedy for various diseases (Kanaanite, 1940. pp. 15, 28, 57, 94, 98).

The main part of the text focuses on the medicinal properties of food products, both plant-based and from various animal or bird meats. It is also important to note that the main types of meats, fish, fruits and vegetables, herbs, and grains are similar to those found in Western European cuisine. Additionally, game meat was also used for food. Whenever similar parallels are found, we have attempted to identify analogies in both Georgian and European treatises regarding the medicinal uses of the same foods.

In addition to wine, analogies also emerge regarding other beverages, such as rose water (infusion). Ustsoro Karabadini suggests that if a person is suffering from a headache and fever, rose water can be used to cool them down: "Pour rose water [...] embrocate it, then spread it on clothing and apply it to the head" (Kanaanite, 1940, p. 26). Similar recommendations for rose water can be found in the Tacuinum Sanitatis (The Health Calendar), a treatise widely circulated in medieval Europe (Hoeniger, 2006). The medicinal properties of rose water are noted in the three editions of the treatise—Parisian, Roman, and Viennese—and the text is identical: “Rose water is beneficial for headaches caused by brain inflammation” (Cogliati Arano, 1976, pp. 80–81).

Among edible plants, garlic was recognized for its broad medicinal properties. According to the treatises mentioned earlier, garlic was believed to possess numerous healing qualities, leading to many analogies. In Ustsoro Karabadini, it is stated that “garlic heals stomach ailments and removes harmful fluids from the body. It also helps with bites from snakes, scorpions, and rabid animals” (Kanaanite, 1940, p. 441). A similar reference can be found in the works of the 3rd-century Roman author Quintus Gargilius Martialis in medieval editions, where it is noted that “garlic protects a person from the harm caused by snakes, scorpions, and other dangerous creatures” (Maire, 1997; Gargilius Martialis, 2002; Wallis, 2010). A brief mention of garlic as an antidote to poison appears in the Roman and Rouen editions of Tacuinum Sanitatis (The Health Calendar) (Cogliati Arano, 1976, p. 116).

Almonds also stand out for their wide medicinal properties, which are given considerable attention in the written works we mentioned earlier. According to The Ustsoro Karabadin, “It opens the paths of the liver and lungs, relieves abdominal pain [...] and helps with kidney pain. [...] Eating it with honey cleanses the heart, lungs, liver, and kidneys” (Kanaanite, 1940, pp. 455–456). The combination of almonds and honey, which is said to cure diseases of the kidneys, stomach, and liver, is also discussed in the medieval edition of the treatise by Gargilius Martialis mentioned earlier: “Crushed and mixed with honey, it is good for coughs and colitis. [...] Its decoction alleviates pain in the liver and kidneys” (Gargilius Martialis, 2002, pp. 73–74). Similarly, the medicinal properties of almonds are described in the medical treatise by the German nun, St. Hildegard of Bingen (1098–1179). The Benedictine nun created invaluable written works, one of which, Physica, states: “If someone suffers from lung problems or has a weak liver, they should eat almonds often, both raw and cooked. It strengthens the lungs” (Hildegard of Bingen, 1998, p. 120).

An interesting parallel emerges regarding the medicinal properties of egg whites. In The Ustsoro Karabadini, it is advised that anyone with a hot head and forehead can use egg whites for medicinal purposes: “Grind coriander, mix it with egg white, and apply it to the head and forehead” (Kanaanite, 1940, p. 173). The use of egg whites, along with herbs, as a medicinal remedy is also suggested by the Patriarch of Jerusalem, Elias, and King Alfred the Great of Wessex (871–886), who was known for his fragile health. The medical recommendation addressed to the famous Anglo-Saxon monarch includes information stating: “Mix herbs with egg whites, [...] use this balm against all weaknesses of the human body, especially against fever and hallucinations” (Cockayne, 1865, p. 288).

In addition to the analogies mentioned above, several minor similarities in the medicinal properties of different plants have been identified. These similarities are not insignificant, especially considering that we have only presented one Georgian medical text. Now, we should focus on the reasons behind these similarities.

Conclusion.

First and foremost, it is important to note that both Ustsoro Karabadini and the European medical texts referenced in this article are based on Greek and Roman medical traditions. A clear example of this is the mention of Hippocrates (Kanaanite, 1940, pp. 11, 18, 23) and Galen (Kanaanite, 1940, pp. 11, 29, 33, 45, 54) in Ustsoro Karabadini. Therefore, it can be asserted that, like the European medical tradition, Georgian medicine was also grounded in Greek-Roman practices.

The second factor to consider is the impact of Eastern, especially Arab, medical traditions. Considering the extended political and cultural influence of the Arab world in the Georgian region, it is understandable that Georgian medical practices were affected by this. This influence might account for the resemblances with Italian and Spanish medical treatises, as both the Iberian and Apennine peninsulas had significant, direct connections to the Arab world.

The third factor is the shared foundation of Christian traditions in medieval Georgian and European societies. Additionally, similar agricultural practices developed in both regions, influenced by comparable geographical environments. This facilitated the cultivation of crops such as vines, wheat, and others. Over time, the interaction with these plants and the observation of their properties likely led to similar conclusions about their medicinal benefits in isolated societies.

It is worth noting a brief yet significant passage from Isidore of Seville's treatise, in which he writes: "In Iberia, which lies to the east near the Pontus, adjacent to Armenia, many types of herbs grow, which are used in medicinal infusions" (Lindsay, 1911, p. 119; Kutalia, 2004). This passage highlights the recognition of Georgia's geographical space and its diverse natural landscape, as well as its medicinal plants, which were known since classical antiquity and passed on to the European world during the Middle Ages.

In summary, it can be said that the medical treatises of medieval Georgia and Europe share many common characteristics, including:

1. Both medieval Georgian and European societies were based on classical ancient (Greek-Roman) traditions, which also influenced the medical field.
2. Georgian and European medicine were both impacted by Eastern, particularly Arab, medical traditions.
3. Georgians and Europeans, as agricultural societies in similar geographical environments, interacted with many common plant cultures, through careful observation of these plants, they arrived at comparable insights regarding their properties and uses.

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Порівняльний аналіз середньовічних грузинських та європейських медичних трактатів і засобів

Анотація. *Практика медицини в Грузії має корені в давнину та тісно пов'язана з медичними традиціями стародавньої Греції та Риму. Це багате наукове надбання яскраво відображене у ранніх середньовічних грузинських медичних традиціях. У середньовічних грузинських історичних джерелах містяться спеціалізовані медичні тексти та трактати, які свідчать про високий рівень медичних знань того часу. Серед цих текстів особливе значення має грузинський медичний текст XI століття «Уццоро Карабадіні» («Неперевершений медичний довідник»), що є оригінальним грузинським медичним трактатом, який поєднує як грузинський медичний досвід, так і знання з давньої та середньовічної європейської медичних традицій. Паралелі між цим текстом і західноєвропейськими медичними трактатами очевидні з самого початку. Текст містить Гіпократівсько-Галенівську концепцію чотирьох темпераментів, описуючи хвороби, пов'язані з кожним із них, та відповідні методи лікування. Додатково «Уццоро Карабадіні» пропонує рекомендації щодо здоров'я, засновані на сезонних змінах, описуючи виклики, з якими стикається людське тіло протягом року, а також даючи поради щодо подолання хвороб і правильного харчування. Трактат також містить важливі відомості про вагітність, визначення статі дитини та практики догляду за немовлятами. Особлива увага приділяється збалансованій дієті, де детально описано правильне вживання рослинної та тваринної їжі. Відзначається також розділ, присвячений лікувальним властивостям вина – темі, глибоко вкоріненій як у грузинській, так і в європейській традиціях, де вино тісно пов'язувалося з повсякденним життям та сакральним значенням християнських ритуалів. Аналіз цих трактатів чітко демонструє, що подібно до Європи, Грузія розвивала сільськогосподарські практики, особливо культивацію винограду та зернових культур. Історичні та археологічні дослідження підтверджують, що традиції вирощування винограду та пшениці на Кавказі сягають неолітичної епохи. Територія Грузії вважається одним із найдавніших центрів виноградарства та землеробства. Аналіз медичних трактатів показує, що тривале залучення цих аграрних практик як у грузинському, так і в ширшому європейському контексті сприяло відкриттю подібних лікувальних властивостей, пов'язаних з цими культурами. Порівняльний аналіз «Уццоро Карабадіні» та європейських медичних трактатів свідчить, що грузинська медицина була суттєво під впливом як європейських, так і давньогрецько-римських медичних традицій, поділяючи з ними багато спільних рис.*

Ключові слова: *Середньовіччя; медична книга; Грузія; медичні трактати; Уццоро Карабадіні*

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The strategic and technological impact of radar in World War II

Abstract. *Radar technology played a pivotal role in shaping the military strategies and operational dynamics of World War II (WWII), revolutionizing both defensive and offensive capabilities. This study provides an in-depth exploration of the evolution of radar, tracing its theoretical underpinnings in electromagnetic science and its subsequent development into critical wartime technology. The paper examines the major advancements that transformed radar from an experimental concept into an* *indispensable military asset, including the British Chain Home system, the German Freya and Würzburg radars, and the American SCR-270 and H2S systems. These innovations redefined air defense, naval warfare, and ground-based operations, granting unprecedented advantages in surveillance, interception, and target acquisition. The study highlights the strategic significance of radar in key WWII battles, such as the Battle of Britain, the Battle of the Atlantic, and the Pacific Theater, where early detection of enemy movements proved decisive. Additionally, the research delves into the technological race between the Axis and Allied powers, emphasizing the role of scientific ingenuity, intelligence-sharing, and industrial production in accelerating radar development. The integration of radar into aircraft, naval fleets, and ground-based anti-aircraft defenses exemplifies how nations leveraged this technology to gain a tactical edge. Beyond WWII, the study explores how radar innovations extended into the post-war era, influencing the development of modern air traffic control, missile defense systems, weather forecasting, and autonomous navigation technologies. The paper underscores the enduring legacy of radar, demonstrating its dual impact as both a wartime breakthrough and a foundation for contemporary applications. By offering a comprehensive historical and technical analysis, this research underscores radar's crucial role in the evolution of military tactics, technological progress, and global security frameworks.*

Keywords: *radar development; Second World War; electronic warfare; Chain Home*

Introduction.

Technological advancements have often been accelerated by war, particularly in conflicts such as World War II (WWII), where strategic needs drove progress across various fields, including computing, chemistry, energy, and communications. This paper focuses specifically on radar technology, examining its transformative impact on military strategies and its role in shaping key wartime outcomes. These wartime innovations reflect the urgent need to address immediate military challenges, leading to breakthroughs that would have taken much longer in peacetime. Radar exemplifies how wartime pressures transformed technological potential into strategic advantage, reshaping military tactics and altering the war's course. Its rapid development and deployment reflect the intersection of innovation and necessity in warfare (Brown, 1999; Reed, 2014).

Radar, an acronym for Radio Detection and Ranging, emits electromagnetic pulses reflecting off objects. By measuring the time the reflected signals return, radar systems determine the object's distance and location. Additionally, the Doppler effect detects frequency shifts in the reflected signal, enabling the calculation of an object's velocity. Key factors influencing radar performance include wavelength, signal-to-noise ratio (SNR), antenna design, and polarization. Shorter wavelengths provide higher resolution, while longer wavelengths reduce atmospheric interference. High

SNR ensures accurate detection and advanced antenna designs enhance directionality and beam steering (Jain & Heydari, 2013; Zimmerman, 2013).

This study highlights radar's direct influence on pivotal WWII engagements, such as the Battle of Britain and the Battle of the Atlantic, where early detection systems and naval radars decisively shaped military tactics. By bridging technological advancement with strategic execution, radar not only provided tactical advantages but also influenced the broader trajectory of the war. Early radar systems faced significant challenges, particularly noise interference that limited their precision, necessitating intense research to improve their performance. By the onset of the war, these efforts had revolutionized radar, making it a vital military tool for detecting and tracking enemy aircraft and ships. The British Chain Home (CH) radar network exemplified radar's critical impact on military strategy, providing early warnings of Luftwaffe attacks and enabling precise defensive coordination. Similarly, radar systems used in naval engagements and anti-submarine warfare transformed tactical planning by providing real-time information critical for decision-making (Blanchard & van Genderen, 2014). Post-war innovations, such as those introduced by Woodward in the 1950s (Woodward, 1953), further optimized radar by reducing noise and improving cost-effectiveness, paving the way for broader applications in meteorology, air traffic control, and space exploration. However, its military applications, particularly in defense, remain predominant (Butt & Jalil, 2013).

From Karl Popper's falsificationism perspective, radar's evolution reflects a process of trial and error. Initial limitations were tested and overcome through practical applications, resulting in increasingly effective solutions (Popper, 2002). Today, continued advancements, including the integration of artificial intelligence, further enhance radar's capabilities in defense, aviation, and weather forecasting (Chernyak & Immoreev, 2009).

By focusing on the scientific origins, wartime applications, and lasting influence of radar technology, this article emphasizes its unique contribution to the evolution of modern warfare and technology. It situates radar within a historical, scientific, and strategic analysis framework, distinguishing itself from existing studies by its comprehensive treatment of radar's dual role as both a technological innovation and a strategic tool. The article is structured to provide a comprehensive exploration of the topic: it begins with the historical and scientific contexts that set the stage for radar development, followed by an analysis of early advancements in Germany, the United States, and the United Kingdom. The paper's core focuses on radar's pivotal role during WWII, illustrating its influence on critical battles and strategies. Finally, the discussion extends to modern radar applications, reflecting on how wartime innovation shapes military and civilian technologies. This structure aims to offer a cohesive narrative of radar's evolution and its enduring significance.

Methodology for Historical Literature Review.

Literature Search: A systematic exploration was undertaken on Google Scholar, employing Boolean operators to refine the search query: ("Second World War" OR "World War II") AND ("radar" OR "electronic warfare").

Inclusion and Exclusion Criteria: The search combines primary sources, academic articles, and historical documents on the evolution of radar during WWII and its impact today. Non-academic sources, duplicate publications, and studies that diverged from the research focus were excluded. Studies in English and Spanish were included to capture the historical significance of radar.

Quality Assessment: The credibility and reliability of selected sources were rigorously evaluated, considering the reputation of journals, authors, and the coherence of presented arguments. A critical examination of the literature identified gaps, contradictions, and controversies in the historical narrative of radar´s development.

Ethical Considerations: Stringent adherence to copyright laws and meticulous citation practices were employed to ensure ethical handling of the literature, respect for intellectual property rights, and acknowledgment of the origin of all extracted information.

From Electromagnetic Theory to Military Innovation: The Birth of Radar.

Radar's development stems from decades of groundbreaking scientific discoveries and technological innovations. It blends theoretical physics with practical engineering to create a transformative tool of modern warfare.

In 1865, James Clerk Maxwell formulated the foundational electromagnetic theory through eight differential equations, later streamlined to four by Oliver Heaviside in 1884. These equations describe the behavior of electric and magnetic fields and predict the existence of electromagnetic waves, forming the theoretical basis of radar (Maxwell, 1865). Maxwell’s work bridged the gap between theoretical physics and practical applications, showing that electromagnetic waves could propagate through space.

In 1887, Heinrich Hertz experimentally confirmed Maxwell's theories by generating and detecting electromagnetic waves. Hertz demonstrated that these waves could reflect off metallic surfaces, a phenomenon that became critical for radar technology (Blumtritt, Petzold, & Aspray, 1994). His work established that electromagnetic waves could be manipulated and harnessed for practical purposes.

Building on Maxwell and Hertz’s discoveries, Guglielmo Marconi significantly advanced wireless communication through experiments combining transmitters and receivers in the 1890s. Incorporating an LC resonant circuit for frequency selection in his wireless telegraph marked a crucial technological breakthrough. Around the same time, Alexander Popov also contributed to detecting electromagnetic waves by designing a radio wave receiver in 1895, though his work primarily focused on weather telegraphy rather than long-distance communication (Marconi, 1909). These innovations demonstrated electromagnetic waves' potential for communication and object detection.

In 1897, Ferdinand Braun's invention of the cathode ray tube revolutionized data visualization, enabling the graphical representation of signals, a key component in radar systems. Meanwhile, in 1904, Christian Hülsmeyer patented the first operational radar system capable of detecting ships up to 3 km away. Contrary to earlier narratives, Hülsmeyer ceased work on his device in the 1910s due to a lack of demand rather than commercialization issues. Telefunken experts at the time dismissed his radio wave detector as impractical, further stalling his progress. The 1920s witnessed incremental progress in radio technologies, including the development of echo systems, radio altimetry, and vacuum tubes. These innovations improved signal generation and detection capabilities, though radar's potential remained limited by frequency constraints and insufficient power. A significant breakthrough came with Albert Hull's 1920 invention of the magnetron, which provided a more robust and stable source of radio waves. Hull's split-anode magnetron generated low-power L-band waves, but its limited stability restricted its practical use. Notably, during the late 1930s, advancements in magnetron technology included the development of the L-band magnetron by Slutskin in Ukraine (then part of the USSR). By 1940, Slutskin's magnetron achieved an output power of 14 kW and served as the power source for the USSR's gun-aiming radar system, Zenit (Kostenko, Nosich, & Tishchenko, 2001). This progress laid the groundwork for the resonant cavity magnetron (RCM), developed by Boot and Randall in the 1940s, which enabled high-frequency, high-power microwave transmissions essential for modern radar (Boot & Randall, 1946; Hull, 1923).

Significant experiments during the 1930s paved the way for radar systems. For instance, Marconi's 1932 microwave transmission between the Vatican and Castel Gandolfo demonstrated the practical use of high-frequency waves for precise communication. In 1937, Hans Erich Hollmann and Rudolf Kühnhold in Germany and Robert Watson-Watt in the United Kingdom (UK) conducted pioneering experiments in radar using advanced magnetron technology (Martin, 1988).

In parallel, the United States, Germany, and the UK accelerated their research into microwave technology, focusing on detecting aircraft and ships. The establishment of the UK's Chain Home system in 1938 marked the first large-scale application of radar technology, setting the stage for its transformative role in WWII.

The foundational discoveries in electromagnetic theory and the subsequent technological advancements of the late 19th and early 20th centuries provided the scientific basis for radar. However, these theoretical principles translated into practical systems during the heightened innovation spurred by military challenges in World War I (WWI) and the interwar period. The following section explores how these early developments were refined and expanded upon, laying the groundwork for radar's pivotal role in shaping the strategies and outcomes of WWII.

Laying the Groundwork: Technological Advancements Leading to Radar in WWII.

During WWI, the introduction of new technologies like poison gas, tanks, and aviation revolutionized military tactics. Initially used for reconnaissance, aircraft evolved into tools for aerial combat and bombing, introducing a new dimension to warfare. Efforts to counter this aerial threat led to the development of acoustic listening devices and primitive detection systems that laid the foundation for more advanced technologies like radar (Brown, 1999).

The interwar period saw rising political tensions and accelerated technological innovation, particularly in military research. The Treaty of Versailles (1919), which imposed severe restrictions on Germany's military capabilities, indirectly influenced the development of radar by encouraging covert technological research, including advancements in electromagnetic waves for object detection. Lessons from WWI highlighted the importance of early detection, prompting nations like Britain, Germany, and the United States to explore electromagnetic waves for detecting distant objects. By the late 1930s, the UK established the Chain Home system, the world's first operational radar network to detect and intercept incoming aircraft. Contrary to earlier descriptions, the Chain Home network operated at a wavelength of 26 meters when it first became operational in 1938, later shifting to 10 meters. The Chain Home Low system used a wavelength of 1.5 meters. Both systems could detect groups of a dozen or more aircraft, providing azimuth and range data, but could not determine elevation (Beevor, 2012; Buderi, 1996).

By the 1930s, radar research had intensified globally, leading to advancements in directionality with parabolic antennas, interference reduction through polarization and frequency filters, and enhanced detection capabilities (Shiers, 1974). These innovations laid the groundwork for radar's pivotal role in WWII, where it became a cornerstone of military strategy. Radar allowed for precise tracking of enemy aircraft, contributing decisively to battles such as the Battle of Britain, where the Chain Home system played a central role. However, the limitations of early radar systems, such as poor resolution in azimuth and the inability to detect elevation, spurred efforts to develop shorter-wavelength technologies, ultimately improving detection precision and reliability (Goss, Hooker, & Ekers, 2023).

As the war progressed, radar countermeasures emerged as a critical area of innovation. Techniques such as "Chaff" (called "Window" in the UK and "Düppel" in Germany) were developed to disrupt enemy radar systems while jamming technology was used to block radar signals (Blake, Philpott, & Guthrie, 1943; Putley, 1986). These countermeasures underscored the dynamic interplay between radar advancement and the ongoing need to neutralize enemy systems, illustrating the constant evolution of electronic warfare strategies (Pun, 2021).

Early Radar Development in Germany, the UK, and the USA.

Germany's Strategic Shift Toward Radar.

Following WWI, Germany prioritized offensive military strategies centered on aircraft, submarines, and tanks, enhancing radio communications to enable rapid, coordinated maneuvers. Initially, radar was viewed solely as a defensive measure to protect coastal regions like the North Sea, and its development was deprioritized (Brown, 1999). However, this perspective shifted in 1933 with the establishment of the Experimental Station for Communication by Telefunken. By 1934, Hans Kühnhold founded GEMA (Gesellschaft für Elektroakustische und Mechanische Apparate) in collaboration with Telefunken and Siemens, marking the beginning of concerted radar research efforts (Buderi, 1996).

In the mid-1930s, GEMA initiated experiments in the microwave spectrum, culminating in the development of the Freya radar in 1937. Initially designed for maritime detection, Freya was adapted for air defense and was first operationally deployed during the Sudeten Crisis in 1938. By 1939, Freya entered mass production, with 2,000 units serving as early warning systems. Germany's strategic advantage in radar stemmed from its early adoption of shorter wavelengths, such as the 2.4 m used by Freya, 0.8 m in Seetakt, and 50 cm in Würzburg systems. These innovations provided higher resolution and detection precision than the longer wavelengths used by other nations (Brown, 1999).

Germany further expanded its radar capabilities with systems like Wassermann and Mammut, which extended detection ranges, and Würzburg and Lichtenstein, designed for anti-aircraft artillery and night combat (Watson, 2009). Integrating Freya and Würzburg radars became the foundation of the Kammhuber Line, an innovative air defense system stretching across Europe. Initially, the line relied on Freya radars for long-range early warning and manually controlled searchlights for bomber illumination. Over time, Würzburg radars were incorporated to provide precise tracking and guidance for night fighters. This layered approach represented a tactical shift in German air defense, with the Kammhuber Line evolving into a coordinated network capable of targeting Allied bombers effectively.

Introducing radar systems on night fighters, such as the Lichtenstein radar, further revolutionized German tactics. These radars enabled pilots to independently detect and engage Allied bombers without relying on ground control or searchlights. This autonomy marked a significant shift in air defense strategy. The Naxos radar warning receiver also allowed German fighters to home in on H2S emissions from Allied bombers. However, its effectiveness diminished as the Allies introduced X-band radars capable of greater precision and stealth (Pun, 2021).

Despite these advancements, the Allies' deployment of shorter-wavelength S-band and X-band radars in 1943 diminished the effectiveness of German systems, marking a turning point in radar warfare. Additionally, introducing Naxos, a radar warning receiver, allowed German night fighters to home in on Allied H2S radar emissions. However, the Allies' shift to X-band radars, capable of detecting periscopes at distances up to 5 miles, rendered Naxos largely ineffective, further undermining Germany's radar capabilities (Pun, 2021).

However, despite these early advancements, Germany fell behind in developing shorter-wavelength technologies, such as the S-band (10 cm) and X-band (3 cm) radars enabled by the British cavity magnetron breakthrough in 1940. By 1943, these shorter-wavelength radars were deployed extensively across Allied forces, providing a decisive technological edge, particularly in anti-submarine warfare and aerial detection (Pun, 2021). Table 1 highlights the technical specifications and applications of these and other radar systems, showcasing their pivotal role in Germany's military strategy during WWII.

The UK's Defensive Focus and Radar Innovations.

In contrast to Germany's offensive strategies, the United Kingdom (UK) pursued a defensive approach, relying on its intelligence services and naval dominance to counter emerging threats. The rise of Hitler and the growing threat of aerial bombardment underscored the need for technological advancements, particularly radar, to safeguard the British Isles (Watson-Watt, 1957).

Despite initial skepticism from the Royal Air Force (RAF), radar emerged as the cornerstone of Britain's defense strategy. Early experiments in the 1920s, such as attempts to develop a "death ray," were abandoned due to limited efficacy. By 1935, Robert Watson-Watt had pioneered the Chain Home (CH) system, the world's first operational radar network. CH stations along Britain's east coast became operational in 1938, capable of detecting aircraft at altitudes of 150 meters and distances of up to 40 km. This system provided early warnings of incoming Luftwaffe attacks, and challenges like multiple detections were resolved with Filter Rooms, enabling efficient differentiation between friendly and enemy aircraft (Buderi, 1996). By 1940, complementary systems like Chain Home Low (CHL) enhanced low-altitude detection capabilities, proving vital during the Battle of Britain (Blanchard & van Genderen, 2014). Radar's role in the sinking of the Bismarck underscores these technological advances. While radar was not the primary means of locating the German battleship, British ship-based radar contributed to tracking its movements. The critical discovery of Bismarck's location resulted primarily from Enigma codebreaking and reconnaissance efforts, including visual spotting by a Catalina aircraft (Watson, 2009).

The UK's collaboration with the United States and Canada through the Tizard Mission in 1940 accelerated radar advancements. The mission introduced critical technologies, including the RCM, which improved radar accuracy and power. Innovations such as the air-to-surface-vessel (ASV) radar further extended radar's applications, particularly in anti-submarine warfare (Berkner, 1946).

The United States Accelerated Radar Development.

Before entering WWII, the United States lagged behind Germany and the UK in radar development due to its lack of immediate offensive or defensive pressures.

However, institutions like the Massachusetts Institute of Technology (MIT) and the Naval Research Laboratory (NRL) laid the groundwork for radar innovation in the 1920s and 1930s. Early systems, including the SCR-268 and SCR-270, demonstrated the potential of radar for early warning and target tracking (Colton, 1945). The attack on Pearl Harbor in December 1941 catalyzed rapid advancements in U.S. radar technology. In 1941, the Airborn radar was still nascent, and the Royal Air Force's first operational airborne radars, like the AI Mark II, lacked microwave capabilities. Subsequent advances, such as the SCR-584 for anti-aircraft targeting and the 10-cm wavelength H2S radar introduced later in the war, demonstrated radar's transformative potential in strategic and tactical operations (Watson, 2009). The SCR-270, which detected the incoming attack but failed due to a lack of response protocols, underscored the need to integrate radar into military strategy effectively.

Radar's influence extended beyond defense, significantly shaping offensive strategies. For example, the RAF's adoption of H2S ground-scanning radars on bombers like the Stirlings and Lancasters enabled precise night raids on German cities, complementing the USAF's daylight bombings. American aircraft, such as the Liberators and Flying Fortresses, initially relied on superior optical aiming systems but later incorporated radar technologies to enhance accuracy. This strategic division of labor, with the RAF targeting at night and the USAF focusing on daytime operations, showcased radar's critical role in coordinating Allied bombing campaigns and maximizing their impact on German targets (Gregory, 2011).

A critical innovation during this period was the introduction of proximity fuses in anti-aircraft artillery. Developed using Doppler radar principles in the UK and refined in the United States after 1940, these fuses automatically detonated shells within a certain distance of their targets. Combined with systems like the SCR-584, they drastically improved the efficiency of anti-aircraft defense, enabling effective countermeasures against fast-moving targets such as V-1 cruise missiles, especially in the defense of London and Antwerp (Goss, Hooker, & Ekers, 2023).

Subsequent developments, such as the CXAM radar for fleet defense and the SCR-584 for anti-aircraft targeting, showcased the United States' ability to leverage its industrial and scientific capacity. The invention of the klystron in 1937 enabled compact radar systems for airborne applications, further advancing U.S. capabilities. As detailed in Table 1, these systems positioned the United States as a radar technology leader by the war's end.

The Strategic Impact of Radar in Key WWII Battles.

Radar's transformative impact on WWII cannot be overstated. Its applications spanned early detection, air interception, ground control, and naval operations, fundamentally reshaping military strategies.

Table 1. Characteristics of the primary radars of WWII.

Radar's name	Country	Year	λ	Power	Range	Type	Use
Freya	Germany	1937	2.4 m	8 kW	130 km	Ground	Early warning of air attacks
Wassermann	Germany	1940	2.4 m	100 kW	300 km	Ground	Early warning of air attacks
Mammut	Germany	1942	2.4 m	200 kW	300 km	Ground	Early warning of air attacks
Seetakt	Germany	1938	0.82 m	8 kW	20 km	Maritime	Detection of ships and aircraft
Würzburg C	Germany	1940	0.53 m	8 kW	25 km	Ground	Anti-aircraft artillery fire control
Lichtenstein C	Germany	1942	0.61 m	1,5 kW	5 km	Air	Detection of ships and aircraft
SCR-268	USA	1940	1.5 m	75 kW	45 km	Ground	Early warning of air attacks
SCR-270	USA	1940	3 m	100 kW	160 km	Ground	Early warning of air attacks
CXAM	USA	1937	1.5 m	5 kW	80 km	Maritime	Detection of ships and aircraft
SCR-584	USA	1943	0.1 m	250 kW	45 km	Ground	Anti-aircraft artillery fire control
Chain Home	UK	1938	10 m	350 kW	300 km	Ground	Early warning of air attacks
Chain Home Low	UK	1939	1.5 m	150 kW	40 km	Ground	Early warning of air attacks
ASV-Mark II	UK	1940	1.7 m	7 kW	58 km	Air	Detection of ships and aircraft
AI Mark IV	UK	1940	1.5 m	10 kW	6,1 km	Air	Detection of ships and aircraft

The Battle of Britain: Radar as the Cornerstone of Air Defense.

The Chain Home (CH) system played a pivotal role during the Battle of Britain, marking the first large-scale integration of radar into air defense. This network of early warning radar stations provided continuous tracking of incoming Luftwaffe aircraft, enabling the Royal Air Force (RAF) to allocate limited fighter resources efficiently. CH radar primarily offered early warnings of large formations of German bombers, allowing Fighter Command to concentrate scarce fighter squadrons on the most threatened directions while leaving less threatened areas uncovered. Though initially straightforward, this revolutionary tactical approach depended on effectively integrating radar data into centralized decision-making. CH radar data allowed the RAF to intercept German bombers before they reached critical targets, preventing widespread destruction. Despite German reconnaissance detecting CH signals in May 1940, the Luftwaffe underestimated its importance, leading to critical miscalculations. Rather than systematically targeting radar stations, German forces focused on bombing urban areas, missing an opportunity to disable the system early in the campaign. This oversight kept the CH network operational, providing the RAF with crucial situational awareness throughout the battle. Complementary systems like the AI Mark IV radar proved decisive in night combat, enabling effective interception of bombers during low-visibility conditions. Combined with CH system intelligence, these technologies allowed Britain to resist the Luftwaffe's offensive, marking a turning point in the war and demonstrating the strategic interplay between radar technology and military operations (Brown, 1999; Watson-Watt, 1957).

Naval Warfare: The Battle of the Atlantic and the Mediterranean.

In the Battle of the Atlantic, radar systems like the ASV Mark II initially struggled against German U-boats operating at periscope depth. However, introducing shorter-wavelength radars in 1943, such as the British RCM, significantly enhanced submarine detection capabilities, transforming the strategic landscape. Aircraft with improved ASV radars effectively neutralized U-boat threats, demonstrating radar’s pivotal role in Allied naval operations. While radar contributed to tracking the German battleship Bismarck, its discovery in 1941 was primarily due to intercepted and decoded Enigma communications. Ship-based radar played a secondary role in maintaining situational awareness during the hunt, but a Catalina aircraft achieved the final sighting through visual reconnaissance (Buderi, 1996; Watson, 2009). In 1941, Sunderland flying boats equipped with longer-wavelength radars (1.7 m and 1.5 m) combined with powerful searchlights effectively disrupted U-boat traffic in the Bay of Biscay, a critical route for German submarines. In response, the Germans introduced the Metox radar warning receiver. However, the advent of S-band (10 cm) radars in 1943 rendered this technology obsolete, tipping the balance in the Allies' favor (Goss, Hooker, & Ekers, 2023). British radar systems, including Type 279 and ASV radars, were instrumental in protecting supply routes and supporting naval operations in the Mediterranean. Meanwhile, German deployments of Freya and Würzburg radars in North Africa strengthened anti-aircraft defenses, although Allied advancements eventually surpassed these systems. During the Battle of Cape Matapan in March 1941, radar’s primary role was in assisting accurate gun aiming during the British night attack on Italian cruisers. Intelligence from decrypted Italian naval codes by Bletchley Park cryptanalysts, including Mavis Lilian Batey, determined the timing and course of the Italian fleet, enabling the ambush. Radar-blind Italian warships were unprepared for the radar-guided attack by British forces, which inflicted significant losses on the Regia Marina (Blumtritt, Petzold, & Aspray, 1994).

The Eastern and Pacific Fronts: Diverging Strategies.

On the Eastern Front, Germany's use of radar evolved as the Soviets gained strength. Freya and Würzburg radars were instrumental in providing early warnings and coordinating anti-aircraft artillery during nocturnal Soviet bombing raids, enabling effective defense of critical areas such as Ploesti's oil fields. These systems were vital in limiting Soviet air superiority, particularly during critical engagements where German radar-guided defenses inflicted heavy bomber losses (Blumtritt, Petzold, & Aspray, 1994). In contrast, the Soviets, facing technological gaps, depended heavily on imported Allied radars like the SCR-584 and GL Mark III, which bolstered their ability to detect and respond to German air strikes, especially in defending Moscow and Leningrad. These Allied systems provided much-needed situational awareness and improved the Soviet military's coordination during critical offensives.

In the Pacific, radar underscored stark contrasts between U.S. and Japanese capabilities. By 1939, U.S. CXAM radars, deployed on aircraft carriers, provided fleet protection and critical early warning against air and naval threats. The CXAM radar's effectiveness was exemplified during the defense of U.S. fleets in the Solomon Islands campaign, where early detection allowed timely countermeasures against Japanese assaults. Japan, by contrast, initially lacked operational radar, relying on inadequate magnetron systems with limited range and power. Although radar was not decisive in battles like Midway, the SCR-270 radar played a crucial role in detecting incoming Japanese aircraft during the Pearl Harbor attack, highlighting the strategic potential of radar technology even under limited protocols. As the war progressed, U.S. radar systems, including the air-to-surface-vessel (ASV) radar, proved critical in isolating Japan by enabling effective submarine attacks on Japanese merchant and military fleets, ultimately contributing to the Allied blockade strategy (Wilkinson, 1946).

Current Radar Applications.

After WWII, radar began to be used in civilian applications. This usage has continuously evolved to the present day. Below are the most important current applications of radar.

Ground-based interferometric radar is widely used for monitoring civil infrastructure, such as bridges, dams, and buildings. This type of radar can detect deformations and structural movements with precision over time, providing critical data for preventive maintenance and safety. The radar's ability to offer continuous, non-contact measurements allows for early identification of structural failures, preventing them from becoming severe hazards. Recent advancements in machine learning algorithms have improved the efficiency and accuracy of data analysis, making monitoring more effective and proactive (Elshaboury, Mohammed Abdelkader, Al-Sakkaf, & Zayed, 2023).

In medicine, radar technology is increasingly used to monitor vital signs and detect diseases. This method enables continuous, contactless heart sound monitoring, facilitating early detection of cardiovascular diseases and reducing patient discomfort. Studies have shown high accuracy in classifying heart sounds using radar, indicating significant clinical potential. Additionally, radar measures vital signs such as respiratory and heart rates in hospitals and homes, providing a non-invasive and comfortable solution for continuous monitoring (Schellenberger et al., 2020).

Radar is essential in detection and ranging systems for autonomous vehicles. It is used to detect objects and measure distances with high precision, which is critical for safe navigation and collision prevention. Unlike other sensors, such as cameras, radar is less affected by adverse weather conditions, making it indispensable in all environments. Studies highlight the combination of radar with other sensors, such as LIDAR and cameras, to enhance the accuracy and reliability of perception systems in autonomous vehicles. This multimodal integration enables a more robust and precise understanding of the surroundings, improving the vehicles' ability to navigate safely and efficiently in complex environments (Liu, Cai, Wang, & Chen, 2021).

Earth observation through radar satellites is essential for environmental monitoring. This technology is used for land-use mapping, detecting environmental changes, and monitoring natural disasters. Radar data is crucial for natural resource management and emergency response, particularly where atmospheric conditions hinder optical observation. The fusion of optical and radar data improves the accuracy and usefulness of information for environmental applications, facilitating better disaster management and ecosystem conservation (Brisco, Mahdianpari, & Mohammadimanesh, 2020).

Conclusions.

The conclusions of this research demonstrate that the development and implementation of radar during WWII played a crucial role in shaping military strategies and outcomes, providing the Allied forces with a decisive technological advantage. Radar's impact extended across multiple theaters, from early detection systems in the Battle of Britain to its transformative role in strategic operations, such as tracking enemy fleets and enabling precise coordination during night battles. This research confirms that radar not only enhanced defensive capabilities but also influenced the offensive strategies of the Allies, shifting the balance of power through technological superiority.

The study's objectives were achieved through a comprehensive analysis of radar's evolution, highlighting its role in accelerating technological advancements in electronics and communication. Key breakthroughs, such as introducing shorter-wavelength S-band and X-band radars, proved instrumental in anti-submarine warfare and aerial detection, ultimately tipping the balance in favor of the Allied forces.

Moreover, the research underscores the lasting significance of radar, not only in WWII but also in its continued influence on modern military and civilian applications, such as weather forecasting, air traffic control, and autonomous vehicle technologies.

The findings confirm that radar development during the war marked a turning point in military history and technological progress. They illustrate the profound interplay between innovation and strategy in shaping the outcomes of WWII. This research further emphasizes the importance of multidisciplinary advancements and international collaboration in driving technological innovation during times of crisis.

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Стратегічний та технологічний вплив радару під час Другої світової війни

Анотація. *Радарна технологія відіграла вирішальну роль у формуванні військових стратегій та операційної динаміки під час Другої світової війни, революціонізуючи як оборонні, так і наступальні можливості. Ця стаття надає глибоке дослідження еволюції радару, прослідковуючи його теоретичні основи в електромагнітній науці та його подальший розвиток у критичну технологію для військових потреб. У статті розглядаються основні досягнення, що* *трансформували радар з експериментальної концепції в незамінний військовий ресурс, зокрема британська система Chain Home, німецькі радари Freya та Würzburg, а також американські системи SCR-270 та H2S. Ці інновації переосмислили повітряну оборону, морську війну та наземні операції, надавши безпрецедентні переваги в спостереженні, перехопленні та захопленні цілей. Дослідження підкреслює стратегічне значення радару в ключових битвах Другої світової війни, таких як Битва за Британію, Битва в Атлантиці та Тихоокеанський театр, де своєчасне виявлення рухів ворога виявилося вирішальним. Крім того, дослідження занурюється в технологічну гонку між воючими сторонами, підкреслюючи роль наукової винахідливості, обміну розвідданими та промислового виробництва у прискоренні розвитку радарів. Інтеграція радару в авіацію, військово-морські флотилії та наземну протиповітряну оборону є прикладом того, як нації використовували цю технологію для здобуття тактичної переваги. Поза Другою світовою війною дослідження також розглядає, як інновації в радарних технологіях перейшли в післявоєнну еру, впливаючи на розвиток сучасних систем управління повітряним рухом, протиракетних систем, прогнозування погоди та автономних навігаційних технологій. У статті підкреслюється незмінна спадщина радара, демонструючи його подвійний вплив як прориву воєнного часу та основи для сучасних застосувань. Завдяки комплексному історичному та технічному аналізу це дослідження підкреслює важливу роль радару в еволюції військової тактики, технологічного прогресу та глобальних систем безпеки.*

Ключові слова: *розвиток радару; Друга світова війна; електронна боротьба; Chain Home*

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Historical background of wood-fired ceramics firing in cross-flow kilns

Abstract. *This work is a comprehensive study that covers the historical, technical and creative aspects of the unique process of wood firing of ceramics. The conducted research allowed to understand the essence of wood firing, its aesthetic and cultural value more deeply. Analysis of the historical development of wood firing revealed its deep roots in the cultural traditions of different peoples. This technique, which originated thousands of years ago, remains relevant due to its ability to create unique textures, effects and emphasize the natural beauty of the material. The historical aspect shows how wood firing has transformed from a utilitarian process into an important artistic tool. A key feature of wood firing is the use of special kilns designed to maintain high temperatures for a long time. Research into different types of cross-flow wood kilns revealed their technical features and impact on the final result. It has been established that the firing process depends on many factors, including the type of wood, the atmosphere of the kiln, the temperature and the duration of firing. These parameters form the unique character of each product. The use of wood firing for artistic purposes allows to achieve unique visual effects, such as natural ash pouring, textured surfaces, natural color transitions. Wood firing is a unique process that*

combines tradition and innovation, technology and art. Its significance lies in the ability to create objects that are not only visually striking, but also carry a deep emotional content. This technique requires skill, patience and understanding of the material, as well as the willingness to work with the element of fire, which becomes a full-fledged co-author. The research conducted not only deepened knowledge about wood firing, but also showed its limitless possibilities for creative expression. The study demonstrates that this technique remains relevant and inspiring for contemporary artists, offering endless opportunities for discovery in the field of artistic ceramics. The technology of wood firing in cross-flow kilns continues to develop, and its capabilities open up new horizons for contemporary ceramic art. Wood firing is not only a technology, but also a philosophy. It reflects the interaction of man with nature and fire, allowing the creation of unique ceramic products that cannot be repeated. This is precisely its value and unfading relevance in the world of ceramic art.
Keywords*: art history; cultural history; history of ceramics; clay; artistic ceramics; kilns for wood-fired ceramics*

Introduction.

Studying the history of the development of ceramics is of great importance, as it allows to better understand the past of mankind. Ceramics are not just clay and fire, but a true reflection of the culture, way of life, technologies and even beliefs of different peoples. Ceramic products are often the only thing left of ancient civilizations, and they help scientists recreate the picture of life in those distant times.

Ceramics are well preserved in the ground, so they play a key role in the work of archaeologists. By its appearance, shape or ornamentation, it is possible to determine when and where it was made, as well as find out who certain peoples traded with or what cultural influences acted on them.

In addition, the history of ceramics shows how technologies developed. Kilns, temperatures, clay composition changed, glazes appeared, new methods of decoration. All this became the basis for many modern materials that we use today not only in everyday life, but also in medicine or even in military affairs (Ałykow, Bednarz, Piechówka-Mielnik, Napiórkowska-Ałykow, & Krupa, 2022; Morito, 2022).

For artists and craftsmen, ceramics are also a source of inspiration. Ancient techniques – for example, wood firing or applying ash glaze – are actively used in author's works today, as they give unique effects that cannot be achieved in any other way.

Finally, studying ceramic heritage is a way to preserve traditions. Many craft techniques are passed down from generation to generation, and thanks to research, they can not only be preserved, but also popularized throughout the world. Some of them are even recognized as part of the intangible cultural heritage of humanity. So, by studying ceramics, we are not just exploring the past – we are learning more about ourselves, our roots, and the development of civilization as a whole.

Ceramics is one of the oldest branches of human activity, dating back thousands of years. The oldest known ceramic artifact dates back to approximately 29,000 to 22,000 years BP, during the Upper Paleolithic. It is a figurine of a woman known as the Venus from Dolni Vestonice, (Figure 1), from a small prehistoric settlement near Brno in the Czech Republic (Potvin, 2024).

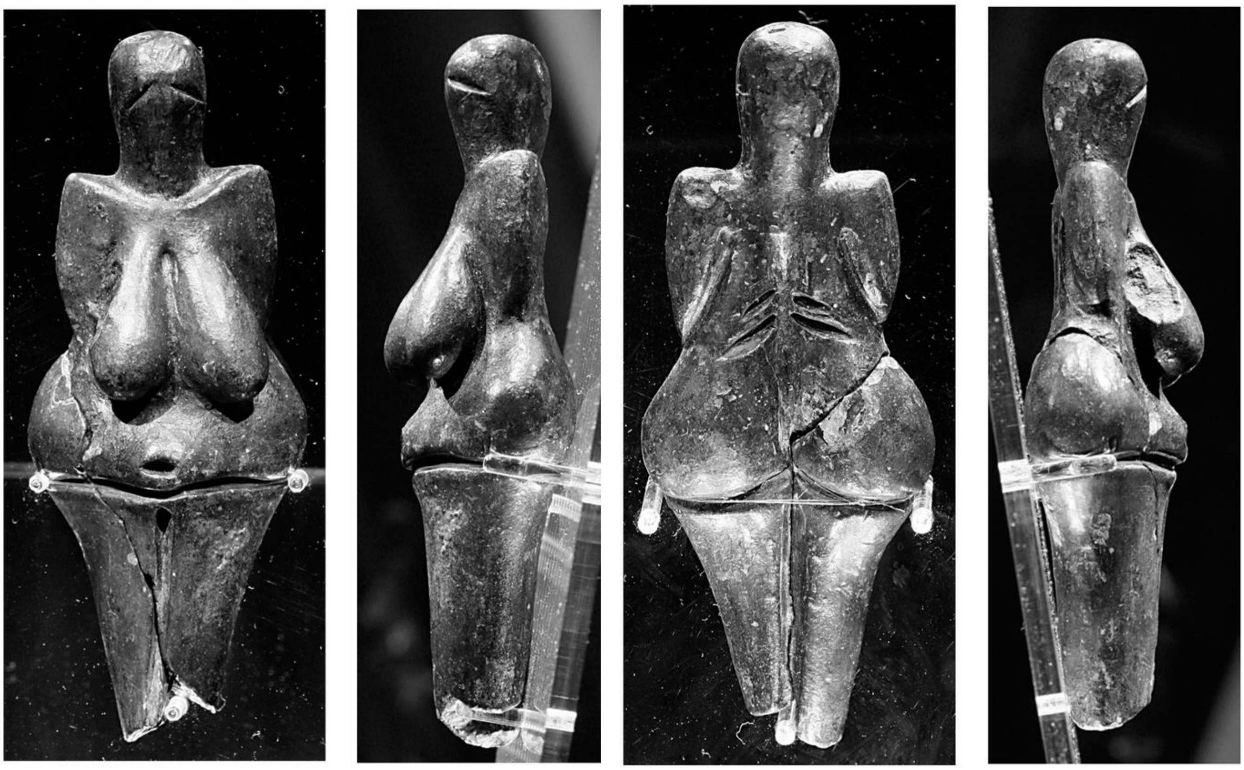

Figure 1. Venus from Dolni Vestonice, 29,000 to 22,000 years BP (Potvin, 2024).

Wood firing is one of the oldest ceramic techniques, dating back to prehistoric times. This process, which involves the use of fire to fire clay, has evolved across cultures and regions around the world, each bringing its own unique style to the firing process. Wood firing dates back to the Neolithic period (about 10,000 years ago). The first ceramics were made in primitive pits (Figure 2), where the clay was first shaped by hand and then fired in open fires.

In Mesopotamia, Egypt, and modern-day China, wood-firing was used to produce pottery for ritual, utilitarian, and decorative purposes (Beck, Hill, & Khandelwal, 2022; Bozdemir, 2024; Gardner, Karkanas, Müller, Freestone, & Kiriatzi, 2025). The oldest examples date back to the 4th millennium BC. Such techniques were also known and used in ancient Peru on the Andean coast (Shimada, Goldstein, Sosa, & Wagner, 2003). Egypt was famous for its earthenware products fired in simple kilns. The clay was often coated with colored glazes obtained by reaching high temperatures.

China pioneered the development of wood-firing, reaching extremely high temperatures that allowed the production of porcelain as early as the Shang Dynasty (1600–1046 BC). Chinese ceramists also invented multi-chamber kilns, known as "dragon kilns," which allowed for more even heat distribution (Wang et al., 2018; Karasu, Andaş, & Ak, 2019; Li, Shen, Zheng, & Wang, 2021; Fang, 2023).

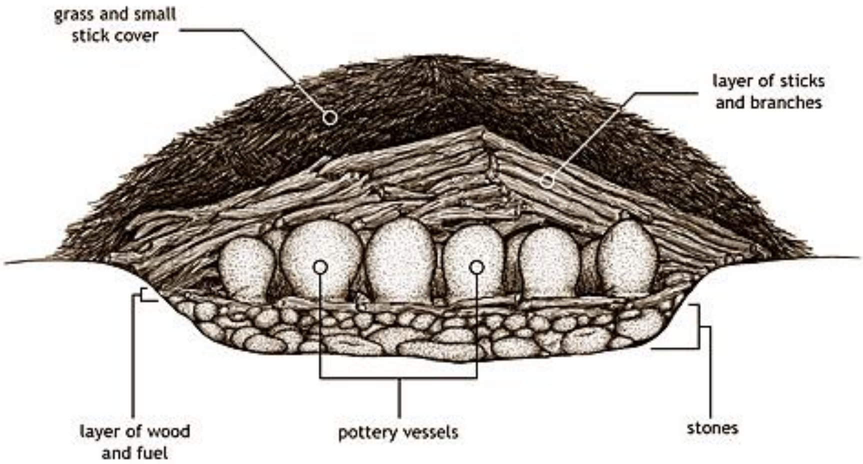

Figure 2. Primitive pottery pit (Brooke, n.d).

In Greece and Rome, the wood-firing technique was widely used to make amphorae, vases, and sculptures. Greek ceramists created the famous black and red figured vases, using special kilns to control the oxidation process and restore the colors during firing (Jones, 2021). Black-on-red painted pottery is one of the most characteristic typological groups that appeared during the final phases of the Late Neolithic (4800/4700–3900/3800 BC) in northern Greece (Kilikoglou et al., 2007). The Romans later adopted this technology and made it widespread.

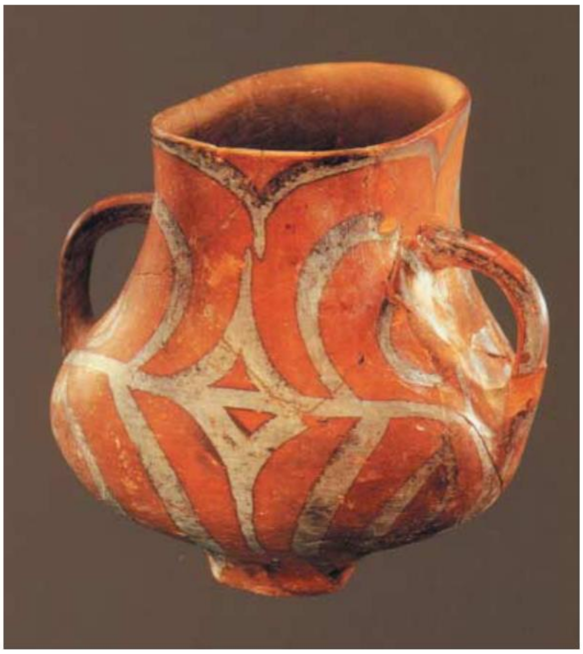

Figure 3. A typical two-handle pot Ancient Greek ceramics (Kilikoglou et al., 2007).

Japan is a pottery powerhouse, boasting an abundance of ceramic production sites all over the country (Web Japan, n.d.). Among these, the six regions of Echizen, Seto, Tokoname, Shigaraki, Tamba, and Bizen – known as the "Six Ancient Kilns" – are said to have been active for more than 1000 years, and were registered as Japan Heritage sites in 2017 (Figure 4).

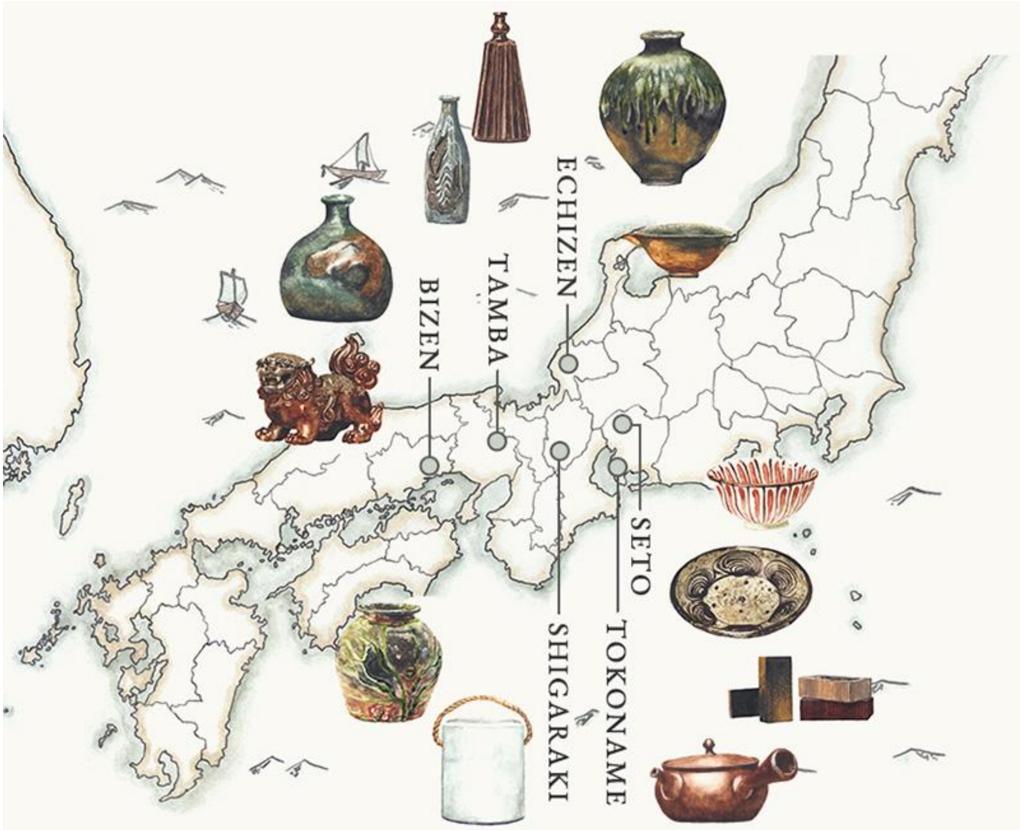

Figure 4. A location map of the "Six Ancient Kilns" (Web Japan, n.d.).

In Japan, wood-fired pottery was particularly developed through the use of Anagama and Noborigama kilns. Among the most famous examples are ceramics from the Momoyama period (1573–1615) (Kilikoglou et al., 2007; Keulemans, 2016; Bergmann, 2020). Japanese craftsmen particularly valued the natural ash glazes that resulted from prolonged firing, which gave the products an organic, natural beauty (Figure 5).

In medieval Europe, ceramics developed through techniques borrowed from the Middle East and China (Qiumei, 2023; Han, Zheng, & Wu, 2021). Wood-fired kilns were used to produce pottery and building materials. In particular, traditional wood-fired kilns such as a Borne kiln in France, the Cassel kiln in Germany and the Newcastle kiln in England were used (Olsen, 2001, p. 59). These kilns often had a multi-chamber design, which allowed firing a large number of products simultaneously. Salt glazes, which were formed as a result of firing with the use of salt, were also popular.

Figure 5. Kuro-Oribe tea bowl (Mino ware, cylindrical form, "Fuyugare ", Momoyama period (1573–1615), 16th century, Stoneware, h. 9.2 cm, d. 10.2 cm. (Kilikoglou et al., 2007).

In Ukraine, kilns were first discovered at the sites of the Trypillia, Chernyakhiv and other cultures (Rud, Zaitseva, Hofmann, Rauba-Bukowska, & Kosakivskyi, 2019; Nikitin, Videiko, Patterson, Renson, & Reich, 2023; Rybicka & Havinskyi, 2023). According to scientists, there were two types of kilns – pottery kilns and pottery horns. These structures differ not only in structure but also in firing technology. Pottery kilns are single-chamber heat-technical structures with a permanent ceiling over the internal volume of the chamber itself, in which the dishes for firing are simultaneously placed and the fire is kindled. Pottery horns are two-chamber heat-technical structures, the upper chamber is called the firing or dish chamber, in which clay products for firing are placed, the lower chamber is the kiln chamber for kindling the fire (Figure 6).

Figure 6. Vyshgorod (Ukraine). Pottery Museum. Pottery horn (Vyshgorod Historical and Cultural Reserve, n.d.).

In the 21st century, wood firing has gained new significance with the studio pottery movement. Potters around the world have revived traditional firing techniques, experimenting with the textures and effects that result from firing clay under the influence of wood and ash. In the United States and Europe, many artists have begun to use wood firing as a form of artistic expression, focusing on natural results that cannot be reproduced using gas or electric kilns.

The aim of the work is a comprehensive study that covers the historical, technical and creative aspects of the unique process of wood firing ceramics, and focuses on the peculiarities of the construction of ancient cross-flow kilns.

Research Methodology.

Studies in the history of science and technology help to see how people in different eras have tried to understand the world and change it with the help of knowledge. They show that many things that seem familiar today were once revolutionary discoveries. Such studies allow to trace how scientific approaches, technical solutions, and engineering thinking were gradually formed (Feng & Liu, 2024; Latsik, Markovych, Hryhoruk, Bazhanov, & Matsyshina, 2024; Strelko, 2021). They also allow to better understand the relationship between science, society, and culture. To investigate this, scientists use historical documents, archives, old drawings, and personal letters of scientists and engineers (Grifa et al., 2021; Pongwisuthiruchte & Potiyaraj, 2025; Strelko et al., 2019). They often also analyze artifacts – from ancient tools to industrial equipment. One important method is to compare the development of the same idea or technology in different countries or eras. Researchers also communicate with modern scientists and technicians to better understand the essence of certain processes. Such interdisciplinary approaches allow to combine knowledge from history, science, technology, and philosophy (Andriiashko, Bilyk, & Kostiukova, 2022; Khyzhynskyi, Lampeka, & Strilets, 2024; Shelyagin et al., 2021). As a result, we get a holistic picture of how humanity learned to think, build, discover, and rethink the world around us.

In this study, we tried not only to describe the history of wood-fired ceramics, but also to understand more deeply how this technology developed in different cultures and why it retains its significance even today. To achieve this, we used several approaches and methods that helped collect, analyze, and summarize information.

First of all, a significant number of sources were processed – from scientific articles, archaeological reports and monographs to publications by contemporary ceramists. We focused on texts that relate to the history of ceramics in the context of wood-firing technology, as well as studies of individual regions (e.g. Japan, China, Europe). This made it possible to trace how the technique changed over time and under what conditions its local variants emerged.

We compared examples of wood-firing from different eras and countries, paying attention to kiln designs, types of wood, firing duration, and ways of placing products in the kiln. This helped to see both common features (e.g. the use of ash as a natural glaze) and culturally specific differences that reflect local traditions and ideas about beauty.

Since the result of wood-firing is always unique, we carefully studied photographs and descriptions of ceramic products created at different times. Color, texture, ash streaks, flame traces were evaluated – everything that helps to understand the specifics of this type of firing. In some cases, data from museum catalogs and online archives were used.

Particular attention was paid to the experience of modern ceramists working with wood-fired kilns. Personal blogs, interviews and video materials were analyzed, in which masters share their vision of the process, difficulties and creative results. This allowed to combine a historical perspective with real practical experience.

To clarify individual technical points (for example, temperature regimes, types of kilns, chemical processes in glaze), we consulted with specialists in the field of ceramics, materials technology and art history.

In general, the work combined historical, cultural and technical approaches. This allowed for a comprehensive consideration of wood firing not only as a method of firing clay, but as an important cultural phenomenon that connects man, nature, and fire in the process of creation. Catalogs, websites, and personal pages of artists involved in wood firing ceramics also became important sources of information.

Results and Discussion.

Crossdraft kilns are classified by the movement of fire from a firebox in one part of the kiln, through a chamber to an outlet in the opposite part (Olsen, 2001; Lu et al., 2012; Ma, Henderson, Evans, Ma, & Cui, 2021). The most common kiln types are the single-chamber kiln, the cave kiln, the stepped tunnel kiln, and the flat tunnel kiln. Crossdraft kilns originated in the Far East.

The exact location and time are unknown, but scholars suggest that ceramists in China, Korea, and Japan invented similar kilns, known as hole kilns, at about the same time (Lu et al., 2012; Li, 2015; Ma, Henderson, Evans, Ma, & Cui, 2021). Hole kilns were used during the Asuka period in Japan, the Sui Dynasty (581–618 AD) in China, and the Silla period in Korea. In Japan, they were called "anagama", where "ana" means hole or cutout, and "gama" means kiln (Figure 7).

Kilns of this type were built directly inside the clay deposits. A hole was dug in the clay hill, an expanded firebox was formed inside the hill, which narrowed again, turning into a chimney. After forming such a kiln, the drying process of the structure took place. The next stage was the first firing of the empty kiln, a fire was continuously burned in the kiln for several days, gradually increasing its intensity until the inner walls of the kiln became strong (burnt to scrap). The Anagama kiln is characterized by the lack of physical separation between the combustion chamber and the firing chamber. Firing wood creates a high temperature and a unique glaze on each product. Firing in an Anagama kiln with wood is important for creating unique ceramic products. A large amount of wood was used during the process, which led to intense burning and the generation of high temperatures of over 760º C/1400º F (Ceramicartis, n.d.). The wood was burned, and the resulting ash was drawn through the chamber into the chimney. This ash settled on the ceramic products, creating a unique glaze on each of them. The presence of ash in this Japanese kiln significantly influenced the final result of the ceramic products. The chemical composition of the ash, combined with the high temperatures, led to complex chemical reactions on the surface of the product. This process created vitrification effects, creating glazes with unique colors and textures on each product, which gave the ceramics fired in the Anagama kiln a special imprint.

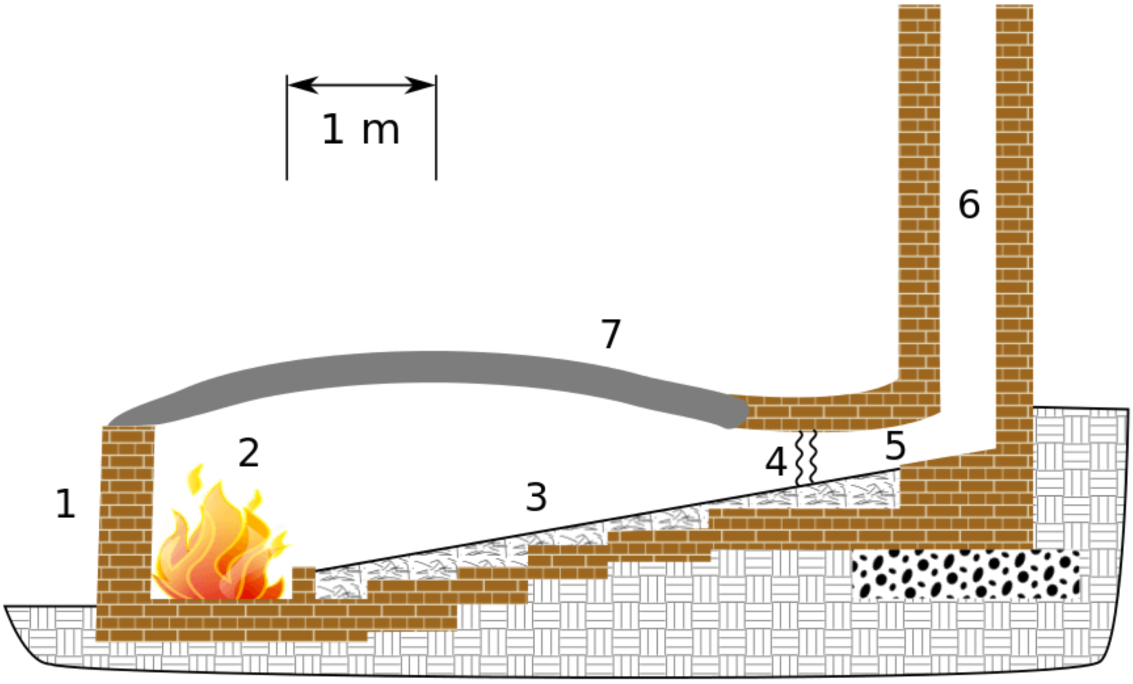

Figure 7. Anagama: The traditional kiln of Japanese ceramics.1 – door approximately 75 cm wide; 2 – firebox; 3 – stacking platform made of silica sand. here the unfired pieces are placed; 4 – two dampers, one for firing and the second for closing the chimney hermetically; 5 – flue; 6 – fireplace 3 meters high; 7 – cast arc, made of heat-resistant (castable) cement (Ceramicartis, n.d.).

Among the cross-flow kilns, the following striking examples can be distinguished.

The Tamba tube kiln, which is considered one of the oldest kilns in Japan (Geisinger, 2010; Lee, 2024). Over the past 650 years, the design of the kiln and the firing process in it have remained unchanged and are protected by the Japanese government as cultural heritage. The Tamba kiln, consisting of 23 interconnected segments, was built in the early Kamakura period (1185–1392) by potters who had emigrated from Korea and were engaged in the production of ceramics in the Tachikui region of Japan (Olsen, 2001, p. 50). These potters were tasked with designing a kiln that could simultaneously fire 500 large storage vessels (approximately 65 cm high). The solution was to extend the standard Anagama kiln design to approximately 36.5 m in length and to build a kiln dome above the ground, forming a chimney filled with ceramics (Figure 8).


Figure 8. Kiln pipe Tamba (Japan Travel by NAVITIME, n.d.).

Tamba kilns are of the anagama type, tunnel kilns dug into the hillside, using natural draft to distribute heat evenly. Tamba kilns have a sloping tunnel that allows fire and hot air to move naturally up the slope. They often had multiple chambers for longer firing times. Pottery in such kilns was fired unglazed or with a natural glaze that was formed by ash deposits and chemical reactions at high temperatures.

The wares in such Tamba kilns were placed in rows between side openings. Olsen described the design features of this kiln as follows (Olsen, 2001, pp. 50–51):

> *"Proper loading of the kiln was already an important step, as it played a significant role in the movement of the fire through the kiln during firing. The kiln loader had to crawl inside through the firebox and gradually fill it with wares, starting from the far section. Between the sections, a free space was left for burning wood, which was thrown through the side openings. The design of the kiln allowed the fire to move freely through the pipe thanks to internal chimneys before entering each individual section. The firebox is located in front of the internal chimney in the first section (Figure 9). The firing process began with a small hearth at the edge of the kiln, which gradually increased to accumulate coal, which was slowly pushed into the kiln with a long metal tool. The filling of the kiln took place over 36 hours, which raised the temperature of the first 4 sections to 1000 °C, at this stage the main firebox became an opening for oxygen access, and the addition of*

firewood for burning took place through the side openings in the following sections. It was considered that the required temperature was reached in each individual section when a column of flame of approximately 30 cm emerged from the chimney, after which the flame was allowed to burn out and moved to the next section. Firing continued until the side openings of all sections were filled and the required temperature was reached, due to which a large amount of ash deposits and other fiery effects accumulated on the products. Then the kiln was preserved for slow cooling".

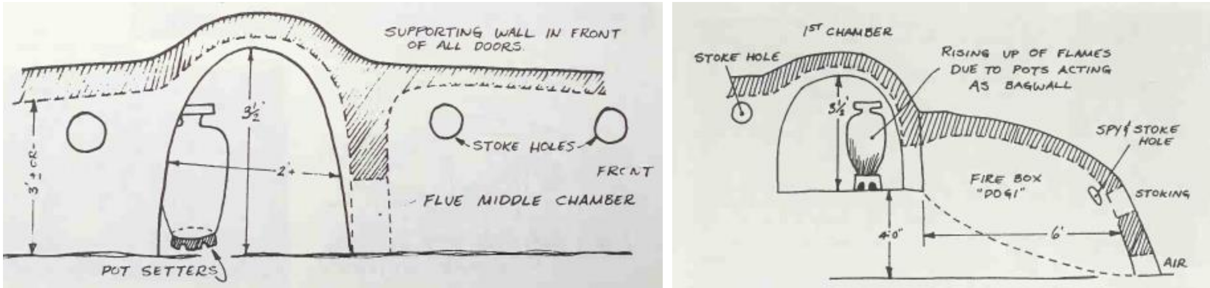

Figure 9. Tamba kiln design (Olsen, 2001, pp. 52–53).

Ceramics made in Tamba kilns have always been valued for their natural, "alive" appearance – ash deposits, flame-induced color changes, dark and reddish tones (Figure 10). This is the effect of the so-called yo-hen – natural variation that is not fully controllable. Today, Tamba kilns are still used by craftsmen who strive to preserve traditional techniques. At the same time, they combine old methods with modern forms, creating works that are valued all over the world. Products from Tamba kilns reflect the aesthetics of wabi-sabi – an appreciation of the imperfect, the changing, the natural. Each piece is unique, with the imprint of the action of fire and smoke.

Figure 10. Ceramics made in Tamba kilns (Japan Travel by NAVITIME, n.d.).

Climbing Chamber Kilns are considered the next step in development after the Tamba kiln, as each section of the kiln became a separate "cave", which allowed for more controlled firing conditions and denser loading (Figure 11). The classic "Climbing Chamber Kiln", or noborigama/dragon kiln, is a multi-chamber, inclined kiln, the structure of which "climbs" up the slope and thereby efficiently uses the heat. Such a kiln was built on a slope with an inclination of approximately 10–16° to effectively use the force of hot air draft. They were developed in China during the Sung Dynasty (960–1279) to assist in the firing of Tenmoku tea bowls in Chienyao, Hohnan and other sites and Celedon wares in the North. The Climbing Chamber Kiln consists of supports and chambers: firewood is burned in the lower chamber, the heat gradually passes through the partitions to the upper chamber, transferring heat – a downdraft design with a counter-flow mechanism.

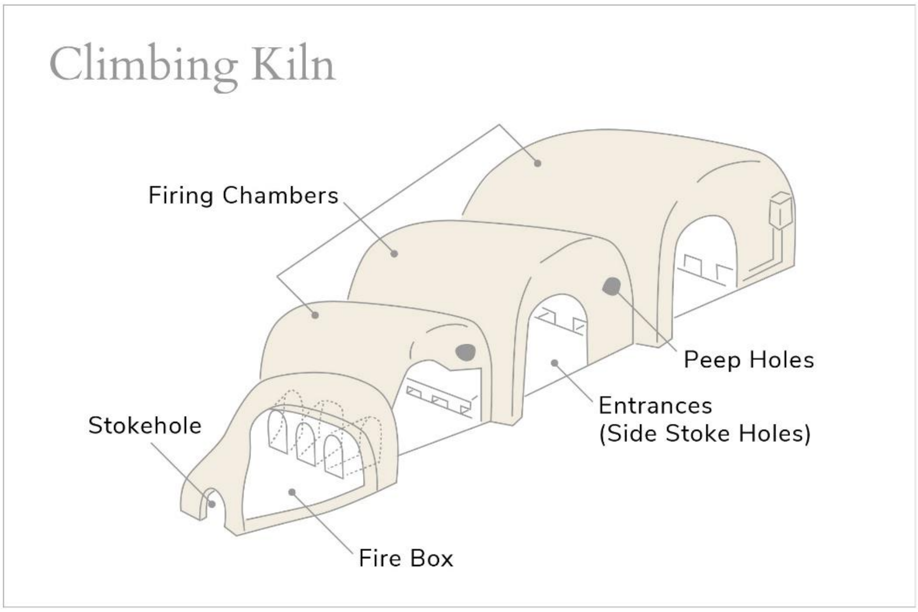

Figure 11. Climbing kiln scheme (Musubi Kiln, 2025).

Each cave had a double radius arch, and the highest point of the arch was shifted to the rear, which slightly complicated the movement of the fire flow and created a reduction atmosphere when the kiln was fired correctly (Olsen, 2001, p. 77). Hot air from the lower chambers heated the upper ones, and the chimney heated the supplied air – this provided a noticeable economy in the use of firewood for fuel. To carry out the firing in the reduction section, it was necessary to constantly maintain a fast rate of firewood supply to maintain a large amount of coal in the kiln. The middle sections had a less radical arch, which facilitated the movement of the fire and contributed to oxidizing conditions (Figure 12). The design of such a kiln provided the possibility of reaching temperatures of 1300–1400°C, with long firings – 2–3 days in a row or even more than a week. By adding firewood separately in each chamber, it was possible to create an oxidizing or reducing environment – this made it possible to simultaneously fire clay products with and without glaze.

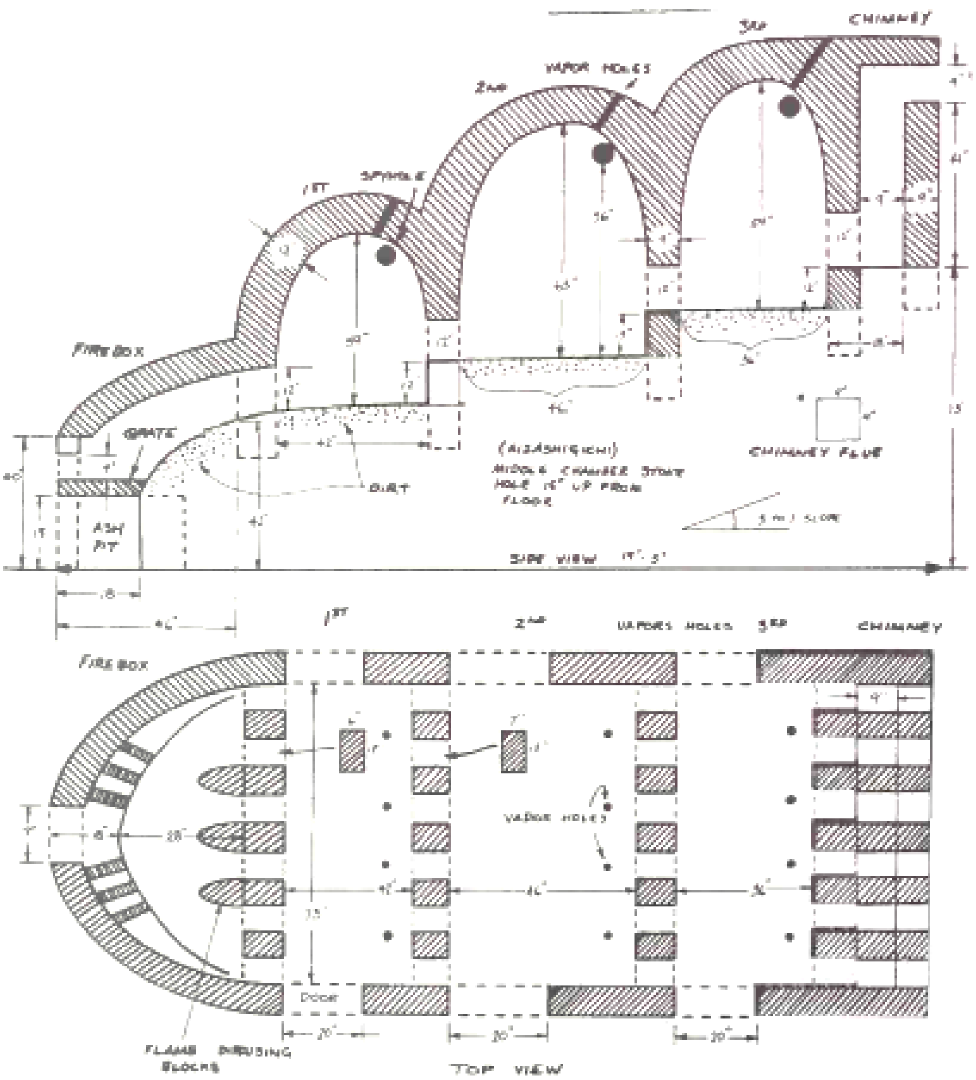

Figure 12. Kyoto Bidai climbing kiln (Olsen, 2001, p. 78).

The noborigama kiln itself is a hybrid of architectural engineering, thermodynamic efficiency and artistic unpredictability (Figure 13). It is a bridge between nature (wood fire), traditional craftsmanship and ceramic aesthetics. Although this approach currently requires significant resources and space, for true connoisseurs of the natural wood-fire spirit, the noborigama is an indispensable tool (Figure 14).

The Bizen kiln is unusual in both function and design when compared to other Japanese kilns, and is only indigenous to the Imbe region of Okayama prefecture in central Japan (Olsen, 2001, p. 83). The features of such a kiln are a large firebox, which allows to increase the surface of direct contact of products with fire, as well as a small air flow in the kiln chamber, which allows to accumulate a large amount of ash, maximized efficiency of wood use during seven-day firing and minimized heat loss during a gradual increase in temperature (Figure 15).

Figure 13. Le Sanpei Climbing Kiln's noborigama (Musubi Kiln, 2025).

Figure 14. Unloading Le Sanpei Kiln's noborigama. Under the electric light, white porcelain glistens atop a column of saggar boxes (Musubi Kiln, 2025).

The hearth of the Bizen kiln is the most open of all Japanese kilns and is the first and most important chamber (Olsen, 2001, p. 84). There is no filling from the hearth to the chimney of the next chamber, only a gradual slope that is interrupted about halfway (Figure 15).

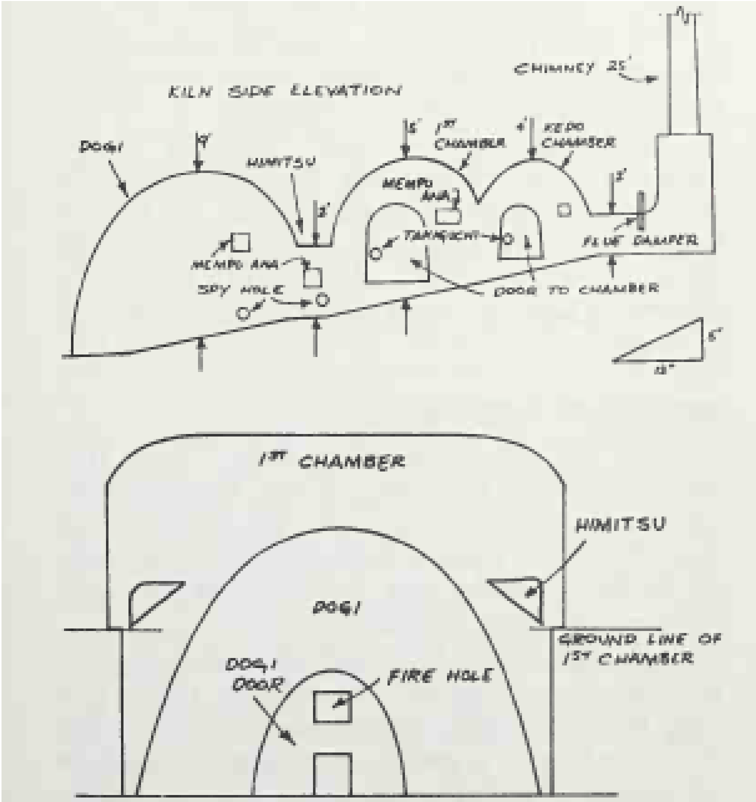

Figure 15. Front and side elevations of the Bizen kiln (Olsen, 2001, p. 85).

This step in the kiln actually consists of shelves on which the wares are also placed. They receive direct contact with the flame and a strong reducing atmosphere containing ash to form a natural ash coating (Olsen, 2001, pp. 83–85). The walls of the Bizen kiln are 25 to 33 cm thick, built tightly, without steam holes and insulated with a layer of a mixture of refractory clay, straw and earth. This thick and dense construction reduces heat loss and ensures intensive heating during a gradual increase in temperature with minimal fuel consumption. Expansion and contraction of the kiln are balanced by the extremely long and gradual firing and cooling cycle. Between the firebox and the first chamber is a 61 cm long chimney, which contains a small chamber called the himitsu, or "secret chamber". The chimney openings leading into the himitsu are very small – 7.5×15 cm, which increases the speed of draft through it to the first chamber. In the himitsu, small items such as tea cups and sake bottles are placed. This chamber is well suited for intensive contact with the flame and ash, since its small size and chimney openings force the fire to pass through the items with a high cross-draft speed. The chimney openings lead from the himitsu to the first chamber. This allows the rapid draft created by the himitsu chimney openings to pass unhindered into the first chamber, without creating back pressure in the himitsu. After entering the first chamber, the draft slows down significantly due to the large volume of the chamber. This chamber has built-in side openings for the takiguchi fire, which help to increase the temperature and create active contact with the flame not only in the lower part, but also in the upper part of the chamber. The second chamber, the kedo, is much lower in height and smaller in width. This chamber does not use shelves; all products are placed on the floor or on top of each other. The chamber has an additional firebox, which, if necessary, is used to increase the temperature.

Ancient Bizen technologies find their new reflection in the works of modern craftsmen. The famous traditional Japanese Bizen ceramic ware is made by firing a certain type of green clay in a wood-fired kiln at a temperature of approximately 1200 °C (Kusano et al., 2021). Bizen ceramics are a simple and unglazed type of ceramics that express two deep and important Japanese concepts: wabi (demonstration of wealth and beauty combined with simplicity or poverty) and sabi (aesthetic sense of solitude). For this reason, great tea masters often used this type of pottery. Bizen pottery is considered an art form that involves the use of both clay and flame, as a variety of colors and patterns can be obtained in the finished products without the aid of artificial glazing or painting (Figure 16).

Figure 16. Traditional Japanese Bizen stoneware produced by Kenji Matsushima, a master Bizen potter. This item had a base and was fired in a firewood kiln (Kusano et al., 2021).

The tradition of wood-fired ceramics was best studied and developed in East Asian countries. Among them are sources on the history of pottery and porcelain in East Asian countries, in particular China, Korea, Japan (Rehren & Yin, 2012; Morito, 2022; Wilson, 2023) and Central Asia (Choriyev, Shaydullaeva, & Raxmonkulova, 2023). Important sources were information about wood-fired, types and designs of kilns, and manuals with advice on wood-fired technology. Recent research and publications on wood-firing ceramics have highlighted several key aspects of the development of the technique, including: wood firing can produce unique aesthetic results, as it creates unique colors, textures, and natural glazes from the ash deposited on the ware during firing. The unpredictability of the process and its impact on the finished product make the technique very attractive to artists, as each piece is unique. The results are influenced by various factors, such as the type of wood, the design of the kiln, and temperature control.

Although wood firing is often associated with randomness, modern craftsmen can predict the results with considerable accuracy through the use of new technologies, such as digital pyrometers and oxyprobes. This allows for the creation of high-quality products with minimal waste. Wood-firing raises environmental issues, including carbon emissions. While the technique itself is not the biggest polluter, modern ceramists are beginning to look for ways to reduce emissions and develop more environmentally friendly approaches to firing.

Conclusions.

Different types of cross-flow kilns for wood-fired ceramics are analyzed, and key kiln designs used in different historical periods and regions of the world are considered. Each of these kilns has its own characteristics that determine the method of temperature control, heat distribution, and firing results. Despite the different design solutions, all of these kilns had a common goal: achieving high temperatures to create strong, waterproof ceramics. The wood-fired process highlights its complexity and uniqueness, based on many variables that determine the final appearance of the products. Wood-firing is not only a technical process, but also a creative art, where every decision affects the result. At different stages of firing – from the initial temperature increase to the final phase of maintaining high temperature – it is important to control the rate of temperature increase, especially when passing through silica inversions (quartz and cristobalite), in order to avoid destruction of the products. Precise control of the temperature and atmosphere in the kiln (oxidative or reductive) allows for the achievement of various aesthetic effects, such as natural ash deposition, the formation of glossy or matte surfaces, and color effects.

An analysis of the historical development of wood firing has revealed its deep roots in the cultural traditions of different peoples. This technique, which originated thousands of years ago, remains relevant due to its ability to create unique textures, effects, and emphasize the natural beauty of the material. The historical aspect shows how wood firing has evolved from a utilitarian process into an important artistic tool.

A study of types of wood-fired kilns, such as Anagama, Noborigama, and others, has revealed their technical features and their influence on the final result. It has been established that the firing process depends on many factors, including the type of wood, the kiln atmosphere, the temperature, and the duration of firing. These parameters form the unique character of each product.

An essential element of successful firing is the time and duration of each stage. Decisions about the duration of high-temperature firing and the rate of cooling directly affect the texture and color of the glazed surfaces. Accordingly, to achieve certain effects, such as the glossy green sheen of a natural ash glaze or complex matte surfaces, the cooling process must be carefully planned.

Thus, wood firing is a complex process, where every choice – from the type of wood to the cooling strategy – creates a unique result.

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The authors declare no conflict of interest.

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Історичне підґрунтя дров'яного випалу кераміки в печах перехресного потоку

Анотація. *Дана робота є комплексним дослідженням, яке охоплює історичні, технічні й творчі аспекти унікального процесу дров'яного випалу кераміки. Проведене дослідження дозволило глибше зрозуміти суть дров'яного випалу, його естетичну та культурну цінність. Аналіз історичного розвитку дров'яного випалу виявив його глибокі корені в культурних традиціях різних народів. Ця техніка, що виникла тисячоліття тому, залишається актуальною завдяки своїй здатності створювати унікальні текстури, ефекти й підкреслювати природну красу матеріалу. Історичний аспект показує, як дров'яний випал перетворився з утилітарного процесу у важливий художній* *інструмент. Ключовою особливістю дров'яного випалу є використання спеціальних печей, призначених для підтримки високої температури протягом тривалого часу. Дослідження різних видів дров'яних печей перехресного потоку розкрило їх технічні особливості та вплив на кінцевий результат. Встановлено, що процес випалу залежить від багатьох факторів, включаючи тип деревини, атмосферу печі, температуру та тривалість випалу. Ці параметри формують неповторний характер кожного виробу. Використання дров'яного випалу в художніх цілях дозволяє досягти неповторних візуальних ефектів, таких як натуральна зольна полива, текстуровані поверхні, природні колірні переходи. Дров'яний випал є унікальним процесом, який об'єднує традиції та інновації, технології та мистецтво. Його значення полягає у здатності створювати об'єкти, які не лише вражають візуально, але й несуть глибокий емоційний зміст. Ця техніка вимагає майстерності, терпіння та розуміння матеріалу, а також готовності працювати зі стихією вогню, який стає повноправним співавтором. Проведене дослідження не лише поглибило знання про дров'яний випал, але й показало його безмежні можливості для творчого самовираження. Дослідження демонструє, що ця техніка залишається актуальною й надихаючою для сучасних митців, пропонуючи нескінченні можливості для відкриттів у галузі художньої кераміки. Технологія дров'яного випалу в печах перехресного потоку продовжує розвиватися, і її можливості відкривають нові горизонти для сучасного керамічного мистецтва. Дров'яний випал - це не лише технологія, а й філософія. Він відображає взаємодію людини з природою та вогнем, дозволяючи створювати унікальні керамічні вироби, які неможливо повторити. Саме в цьому полягає його цінність і незгасаюча актуальність у світі керамічного мистецтва.*

Ключові слова: *історія мистецтва; історія культури; історія кераміки; глина; художня кераміка; печі для дров'яного випалу кераміки*

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Outline of the history of the development of piston aircraft engines charging systems

Abstract*. The subject of the article is a review of the most important facts from the development of supercharging systems for piston aircraft engines from the beginnings of aviation to the present day, with particular emphasis on the period of dominance of piston engines in aviation, i.e. the first half of the 20th century. The work focuses on design solutions developed over the years that had a direct impact on engine operating indicators, altitude characteristic and therefore on aircraft performance. Moreover, in the first chapters it shows the reasons for using supercharging in aviation resulting from the unfavorable altitude characteristics of naturally aspirated engines, low-altitude engines or engines equipped with simple non-altitude superchargers systems. The aim of the article is to comprehensively outline the topic of supercharging piston aircraft engines, including, apart from the history of development, also its prospects. The text was prepared on the basis of literature and primarily on the basis of collected source material such as catalogues, archival publications and catalogue data sets. They allow not only to learn about the solutions used, but also to assess and analyze their impact on the engine's functionality. By learning about the altitude characteristics or operating indicators of an engine, it is possible to assess the usefulness of the design solutions used in its supercharging system. Such work requires not only the work of a historian who relies on source materials to learn about the past, but also the technical knowledge of an engineer who can interpret specific development trends in the construction of machines such as engines and their impact on their operating indicators. This approach allows not only to describe the past, but also to* *learn about development trends over the years. The analysis of historical constructions and operational indicators is often omitted in science because it requires working at the interface of two disciplines, both technical and historical. However, it is important for the development of the history of technology, because it concerns its central subject, i.e. the technical objects themselves.*

Keywords: *supercharging systems; piston aircraft engines; altitude characteristic; engine history*

Introduction.

The aim of this study is to demonstrate the relationship between the constant increase in operational indicators of aircraft piston engines and the use of superchargers in them and the continuous development of supercharging systems.

The first airplanes created at the turn of the 19th and 20th centuries were powered by quite simple piston engines and reached low flight altitudes, usually not exceeding several dozen meters above the ground (Pełczyński, 2023a). In recent years, however, before the outbreak of the First World War, airplanes became increasingly mature functional structures (Angle, 1921), not just sports toys or experimental projects (Lumsden, 1994). Increasing the power concentration of the propulsion units allowed to achieve higher flight ceilings, cruising speeds and range, but this resulted in the emergence of new, numerous construction and operational problems (Smith, 1986).

In aviation, turbosuperchargers and mechanical centrifugal superchargers are mainly used (Głowacki, 2017). The former can provide the most constant altitude characteristics, while maintaining high efficiency at any flight altitude. Their most serious disadvantage is significant thermal loads requiring the use of appropriate materials resistant to high exhaust gas temperatures. Mechanical superchargers are free of this defect. In order to ensure effective charging with a mechanical supercharger in the widest possible altitude range, much more complex systems of two-speed and two-stage superchargers are used than in the case with turbosuperchargers.

The development of aircraft engine supercharging systems had a large impact on operational indicators and the development of aviation in general, which will be presented in this article. Above all, however, it is a general overview, as it presents individual types of superchargers and the genesis of their development.

There are practically no publications solely on the history of the development of supercharging of piston aircraft engines. The subject is discussed in books that are generally about the history of aircraft engines, such as *The development of piston aero engines, from the Wrights brothers to microlights: a century of evolution and still a power to be reckoned with* by B. Gunston (1993), *Aircraft propulsion, a review of the evolution of aircraft piston engines* by C. F. Taylor (1971) or the works of H. Smith such as *A history of aircraft piston engines* (1986). The supercharging systems of specific companies or countries can be found in several publications, including *Allied aircraft piston engines of World War II* by G. White or *Rolls-Royce piston aero engines – a designer remembers* by A. A. Rubbra (1990). However, the most helpful in researching the subject are publications issued in the described era such as *The performance of a supercharged aero engine* by S. Hooker, H. Reed and A. Yarker (1941). The most important source in researching the history of aircraft engines is the *Jane's all of the world's aircraft* series. Each volume, usually published every two years, is a collection of catalog data for every aircraft and aircraft engine produced in the world. Up to 1920, the outstanding source for both engines and early supercharging systems is *Textbook of Aero Engines* by E. H. Sherbondy and G. D. Wardrop (1920).

For research on the development of the design or operational indicators of machines, which are also aircraft engines from an interdisciplinary perspective, based on knowledge from the field of technical sciences and historical sciences, the direct source is the construction itself and operational indicators. Thanks to their interpretation, it is possible to describe the history of development and development trends in a given field. Their knowledge may result from several primary sources. The first is the object itself and possible empirical studies performed on it; the second are source materials such as catalogs, operating instructions, manufacturers' publications, catalog collections, research reports and publications of research results; and the last source are studies and other publications from the period under study in which the necessary information can be found.

Altitude Characteristics of Non-Charged Engines.

The power of piston engines decreases significantly with altitude above sea level. This was observed as early as 1909, when high-altitude flight tests began. The first research on the combustion of fuel in a cylinder at altitude was carried out at the National Bureau of Standards in the USA in 1918 (Taylor, 1971). The decrease in power with increasing flight altitude is similar for all piston engines without supercharging, because it does not depend on their construction, but only on the atmospheric parameters at a given ceiling, and especially on the air density, which decreases with increasing flight altitude. The figure below (Fig. 1) shows just such a decrease in engine power for standard atmosphere (ISA). The data are based on the information from the book "Stosowana mechanika lotu" (eng. "Applied flight mechanics") (Auzan, Bolkhovitinov, Kozlov, Kurickes, & Pysznov, 1938). Based on the book „Teoria silników lotniczych, podręcznik" (eng. "Theory of aircraft engines, textbook") (Worobiow, 1951), information for altitudes above 10,000 meters is given.

Effect of altitude on aircraft speed.

The decrease in air density with the flight ceiling also reduces the drag force. Therefore, often airplane at certain altitudes can reach higher flight speeds than at lower ones. For undercharged and non-high-altitude engines, the maximum speed usually decreases with a slight increase in flight altitude. It is possible that at low altitudes (e.g., up to about 3000 m) the velocity is constant, close to constant or slightly higher in relation to the velocity at sea level. It depends on many factors. For example, the efficiency of the propeller at a given altitude and the characteristics of the drag coefficient of the aircraft for a given Reynolds number. Knowing the parameters of the reference atmosphere, it is possible to derive a simplified dependence of the speed of an aircraft powered by a naturally aspirating engine on the flight altitude (Fig. 2).

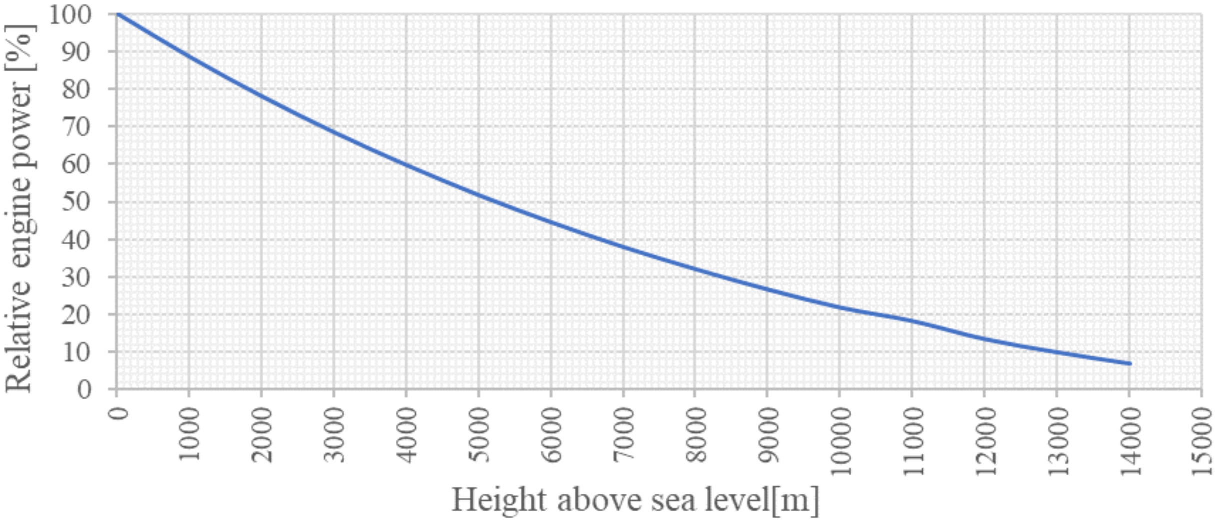

Figure 1. Reducing the relative power of the piston engine at altitude in [%], where 100% is the power at 0 meters (Author's source, based on the *Stosowana mechanika lotu* by A. K. Auzan, W. F. Bolkhovitinov, S. G. Kozlov, J. M. Kurickes and W. S. Pysznov (1938) and on the book *Teoria silników lotniczych, podręcznik* by P. Worobiow).

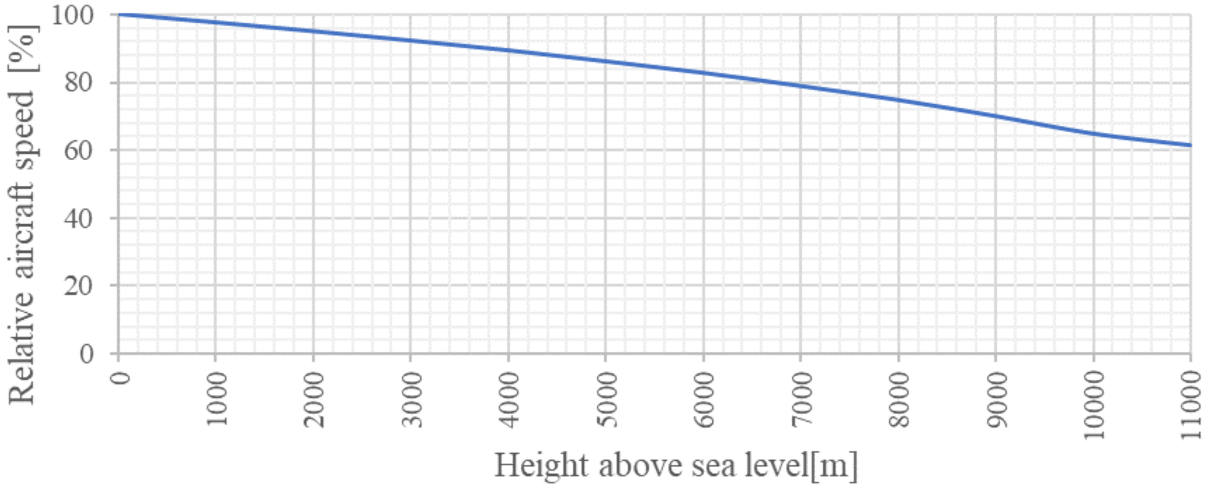

Figure 2. Simplified speed characteristics of an aircraft powered by an undercharged piston engine in [%], where 100% is the aircraft speed at sea level. The figure only includes flights in the troposphere (Author's source, based on the *Stosowana mechanika lotu* by A. K. Auzan, W. F. Bolkhovitinov, S. G. Kozlov, J. M. Kurickes and W. S. Pysznov (1938) and on the book *Teoria silników lotniczych, podręcznik* by P. Worobiow).

In order for the aircraft to climb to a higher altitude, sufficient speed is necessary to maintain lift in the thinned air, which is more difficult to achieve with the decreasing engine power. It is widely known that the lift depends on squared speed according to the formula (1).

$$F_z = \frac{1}{2} \cdot c_z \cdot \rho \cdot S \cdot v^2 \ , \qquad (1)$$

where: F_z – the lift force; c_z – the lift coefficient at the desired angle of attack, Mach number and Reynolds number; ρ – density of air; S – wing surface; v – flight speed (Staszek, 1983).

The thrust of the propeller-engine assembly for a propeller selected for operation in at sea level conditions decreases with altitude due to insufficient engine power. Choosing a propeller with a specific height in mind, in turn, causes an excess of power below this height, which will be too large for the propeller to fully use it. The best solution is to use a propeller with variable blade pitch. This allows it to be adjusted to the flight parameters. The change of pitch can be controlled by the pilot or automatic, regulated by the constant speed controller. It allows not only to set the propeller blades in several positions (usually two), but also to smoothly change the propeller pitch (Worobiow, 1951).

Early Attempts to Solve the Problem of High-Altitude Flights and the Genesis of Aircraft Engine Supercharging Systems.

The first supercharged aircraft engine was built in 1910. It was a two-stroke Murray-Willat equipped with a simple fan that compressed the fuel-air mixture before entering the cylinders (Angle, 1921). It allowed for flight at an altitude of 5,200 meters (Wisłocki, 2023). The second known aircraft engine equipped with a supercharger was built in Japan by Captain Kumazo Hino in 1911. According to the design, it was supposed to achieve a power of 30 hp (22 kW), but in practice only 18 hp (13 kW) was achieved. Probably the same engine was installed in a plane from 1915. However, it managed to increase its power to 25 hp (18 kW). Initially, historians believed, based on photographs, that the engine had four cylinders. However, it turned out that two of them were piston superchargers increasing the air pressure at the inlet to the cylinders (McCutcheon, 2022).

Due to the fact that the first superchargers were only in the experimental phase, the issue of high-altitude flights during World War I was tried to be solved in several ways. In Great Britain, Rolls-Royce used a manually controlled altitude corrector in the carburetors of its engines, which was to ensure the maintenance of a constant composition of the air-fuel mixture.

In Germany, Maybach (Hoffman, 2021) and then BMW designed engines that were supposed to operate at a certain altitude (Sherbondy, Wardrop, 1920). Their entire structure was designed for atmospheric parameters at an altitude of 5,000 meters. However, this did not mean that they were unaffected by the altitude of the flight. In fact, these engines were able to achieve much more power on the ground, but this threatened to damage them due to too significant loads. Therefore, planes equipped with them could not take off with the throttle fully open. Then, in order to fly with maximum power, the pilot could open the throttle while climbing. Too much fuel would result in too high pressures in the cylinders and thus loads on the crank system. The engine maintained the same power throughout, up to the design altitude. After exceeding it, it began to decrease, as in any other engine (Rubbra, 1990).

These problems related to the to the decreasing power of piston aircraft engines needed to be solved. Aa early as 1914, Swiss engineer A. J. Buchi proposed the construction of an aircraft turbosupercharger that would allow air to be compressed at higher flight altitudes in order to preserve engine power. Unfortunately, at that time, the construction of a usable turbocharger was impossible, mainly due to the resistance of materials to high temperatures. During the First World War, many studies and trials were carried out. However, they did not go beyond the phase of laboratory experiments (Taylor, 1971).

More advanced work was carried out on mechanically driven superchargers. The British company Royal Aircraft Factory, in cooperation with Armstrong-Siddley, installed a centrifugal supercharger for a radial engine in 1916. Ultimately, however, it was not suitable for production due to high vibrations. Later, the Royal Aircraft Factory also conducted research on turbochargers (Taylor, 1971). In 1918, the French experimental Rateau turbosupercharger was tested on the R.A.F. 4d engine. The tests were carried out on the R.E.8 aircraft (Lumsden, 1994).

The creation and development of turbosuperchargers.

After the end of World War I, work on mechanical superchargers and turbosuperchargers was intensified (Wisłocki, 2023). In 1918, the US Army Air Force Aircraft Engineering Division commissioned General Electric to design a turbocharger. The experimental model was tested in the Liberty engine (National Air and Space Museum, n.d.a), first on a dynamometer, the same year, and then in flight in 1919. The Le Pere airplane with a turbocharged Liberty engine achieved successive altitude records in 1920, 1921 and 1922. Nevertheless, the drive not adapted to the supercharger from the very beginning, turned out to be very prone to failure. For example, while breaking the record in 1920, one of the connecting rods in the engine broke (Taylor, 1971).

A much more serious disadvantage, however, was that the turbine itself was significantly overheating, which led to damage to its blades. This problem was finally brought to attention in 1922 and soon resolved. The turbine casing was mounted so that it was exposed and could be cooled by the air flowing around the airplane. On this basis, General Electric built many successful turbochargers in the 1920s, 1930s and during World War II (Taylor, 1971).

During World War II, two types of General Electric turbochargers were produced: Type B and Type C. The first one was design for engines with power from 801 to

1400 hp (from 589 to 1029 kW), and the second one for engines from 1801 to 2200 hp (from 1324 kW to 1618 kW). Their construction was similar. The single-stage centrifugal turbine powered a single-stage centrifugal supercharger. Turbine rotational speed was 22,000 rpm. Turbochargers were designed so that the engine could achive the same power at any altitude within a certain specific range. To ensure this, an exhaust gas venting was used. Only during the flight at the maximum altitude, the entire exhaust gas flow directed to the turbine (White, 1995).

In the 1930s and 1940s, only one turbocharged engine was produced and applied in practice outside the United States. It was a self-ignition, two-stroke Junkers Jumo 207 engine (Wisniewski, 2013), which was a high-altitude version of the Jumo 205 engine (National Air and Space Museum, n.d.b). Moreover, very advanced tests were carried out in the USSR, but probably no turbocharged engine was used except for experimental flights (Kotelnikov, 2005). Additionally, trials were conducted in Japan (Goodwin & Starkings, 2017), France and the United Kingdom.

Development of Mechanical Superchargers.

However, mechanically driven superchargers turned out to be much more common than turbosuperchargers. However, the first successful aviation mechanical supercharger was developed later than the first successful aviation turbochargers. In 1925, the Curtiss and Wright companies built their experimental, prototype mechanical superchargers. In 1926, they were first successfully used in Jaguar car engines, and in 1927 in the Pratt and Whitney Wasp aircraft engine. It was a Roots supercharger and was designed by NACA (National Advisory Committee for Aeronautics). It was one of the few successful applications of Roots superchargers in aviation, which were quickly replaced by centrifugal superchargers. In 1927, Lieutenant Champion of the United States Navy, flying a plane equipped with a supercharged Wasp engine, broke another altitude record (Taylor, 1971). Simpler construction and lower thermal loads allowed for the widespread use and continuous improvement of the construction of mechanical superchargers. The economic factor was also important here, as turbochargers were much more expensive.

An example of the development of mechanical supercharging can be Rolls Royce Merlin engine. Initially, it was equipped with a single-stage, two-speed Farman supercharger. Subsequent versions of Merlin had a two-stage and two-speed supercharger. The compression ratio was 9.49:1. Due to high temperatures, the supercharger in most versions had a separate cooling system that used water with glycol (Rubbra, 1990).

The use of two-speed and two-stage compressors allows for approximation of the height characteristics of the supercharged engine to the characteristics of the turbocharged engine (Hooker, Reed, & Yarker, 1941).

In engines with two-stage superchargers, the second stage is usually switched on only at a certain altitude to improve the altitude characteristics of the engine. Single-stage superchargers and the first stages of two-stage superchargers in high-altitude engines achieve compression ratios between 5:1 and 9.5:1. However, there were greater values. An example is the German Daimler Benz DB 601 engine from the Second World War, equipped with a single-stage mechanical supercharger with a compression ratio of 10.47:1. Most two-stage supercharger static pressure ranges from 7:1 to 11:1 (Jones, 1995).

Altitude Characteristics of Supercharged Engines.

The development of aircraft engines supercharging has had a positive impact on the use of other advantages and applications for superchargers. In addition to improving the altitude characteristics of the engines, they allowed to increase the parameters of all piston engines. In airplanes, superchargers turned out to be useful not only for high-altitude flights, but also in order to increase engine power during take-off, flight or air combat (Douglas, 2022).

The advantages of aircraft superchargers are best reflected in the altitude characteristics of the engines. The chart (Fig. 3) shows the characteristics of the Rolls-Royce Merlin engine at different altitudes with two types of supercharging and without supercharging (Gunston, 1993).

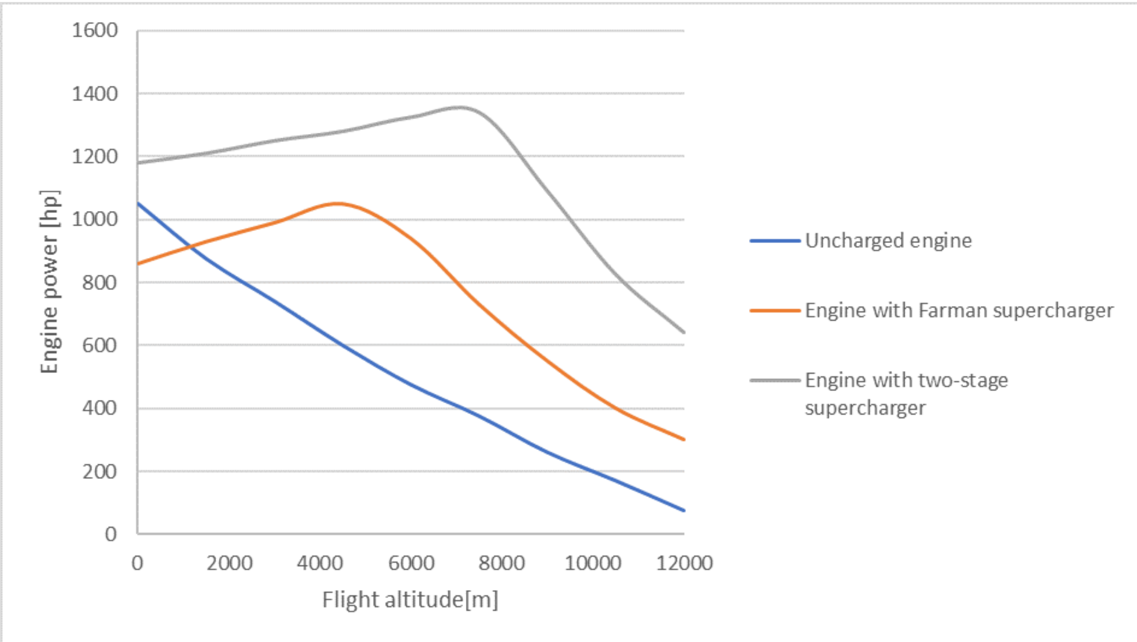

Figure 3. Altitude characteristics of Rolls-Royce Merlin engines in several versions (based on *Rolls-Royce piston aero engines – a designer remembers* by A. A. Rubbra (1990)).

At an altitude of 10,000 m without supercharging it reaches only 200 hp, with a Farman supercharger twice as much, and with a two-stage supercharger as much as 800 hp.

The main problem of mechanical superchargers is the decrease in efficiency with flight altitude. At an altitude of 10,000 meters, it may require up to 30% of the engine power for its propulsion. To prevent this, high-altitude superchargers use complex two-speed and multi-stage systems. Nevertheless, when they exceed the nominal height at which they reach the maximum pressure, their efficiency decreases. Ground-level superchargers have a simpler construction and their task is to supply air under increased pressure, especially at low flight altitudes (Kostia, 1953).

Mechanically driven superchargers are driven from the engine crankshaft, mostly by means of a gear transmission. Belt or chain transmissions, popular in cars, are not used. The superchargers are always centrifugal, although early attempts were made to use Roots systems. Turbochargers are driven by a centrifugal or, less commonly, axial turbine (Balicki, Kawalec, Pągowski, Szczeciński, J., & Szczeciński, S., 2005).

Turbocharger turbines use the difference in exhaust gas and air pressure. At higher altitudes, this difference becomes greater, making turbosuperchargers more efficient at high altitudes than mechanically driven superchargers.

Supercharging and the Fuel System.

Engines with one carburetor have the supercharger located behind the carburetor (sometimes turbochargers may also be located in front of it). The flow of the fuel-air mixture through the supercharger ensures a fairly high degree of mixture evaporation and, importantly, its high homogeneity. The disadvantage of this solution is that the carburetor must be additionally heated to protect it against icing (Balicki, Kawalec, Pągowski, Szczeciński, J., & Szczeciński, S., 2005).

Multi-carburetor engines cannot have a supercharger behind the carburetor, because in such a case there would have to be a separate supercharger for each carburetor. Therefore, it is located in front of the carburetors. This ensures very good evaporation of fuel. In order to obtain the same boost pressure as in the case of a carburetor located in front of the supercharger, less power is needed to drive the mechanical supercharger or less pressure of the exhaust gas feeding the turbocharger turbine. Thanks to this, losses resulting from throttling the exhaust gas flow are smaller. A significant disadvantage of this solution may be uneven air supply to individual engine carburetors, resulting from turbulent flow downstream of the supercharger and upstream of the carburetors. In addition to the flow turbulence caused by the operation of the supercharger, vortices are also formed inside the flow channels, primarily at joints, seals and unevenness of internal surfaces. For this reason, this should be taken into account when designing intake ducts (Wisłocki, 1991).

The use of direct injection instead of a carburetor (Welshans, 2013) allows for more free design of the charging system. Nevertheless, a significant amount of a aircraft engines are equipped with carburetors.

Charge Air Cooling.

In the 1930s, the development of supercharging systems forced the development of effective charge air cooling systems (Wisłocki, 2023). To reduce the risk of accelerated ignition, coolers were used through which air from the supercharger flowed. The simplest solution was to provide external air flow around the radiator.

However, it is usually more effective to use a liquid as a cooling agent (Wisłocki, 1991).

The outbreak of World War II led to the search for solutions that would allow for a more effective increase in power concentration (Bridgman, 1944). In order to be able a short-term increase in boost pressure during air combat, it was necessary to use more efficient cooling systems than those used so far. For this purpose, the phenomenon in which a liquid absorbs part of the thermal energy from the surroundings during evaporation was used (Wisłocki, 1991). The simplest solution was to use water injection into the charge air. It was used in American Allison, Wright and Pratt & Whitney engines (White, 1995) as well as British Rolls-Royce and Napier (Lumsden, 1994). Experiments on water injection were also conducted in the USSR (Kotelnikov, 2005). This solution allows for a short-term increase in engine power. Due to the extra weight of the liquid, it is not possible to use it as a way to cool the charge air for a long periods of time. Moreover, water causes corrosion of engine parts and causes it to wear out faster.

In Germany, water injection was used only in a few types of drives, such as Junkers Jumo 213A and BMW 323R (Bridgman & Gunston, 2001). Due to the greater risk of corrosion, engines equipped with it were inspected every 50 hours of operation. Water injection with methanol was used much more often (Fig. 4, Table 1), as MW 50 (Methanol-Wasser 50%, containing 49.5% water, 50% methanol, 0.5% anti-corrosion agent) or MW 30 (Methanol-Wasser Wasser 30%, containing 69.5% water, 30% methanol and 0.5% anti-corrosion agent).

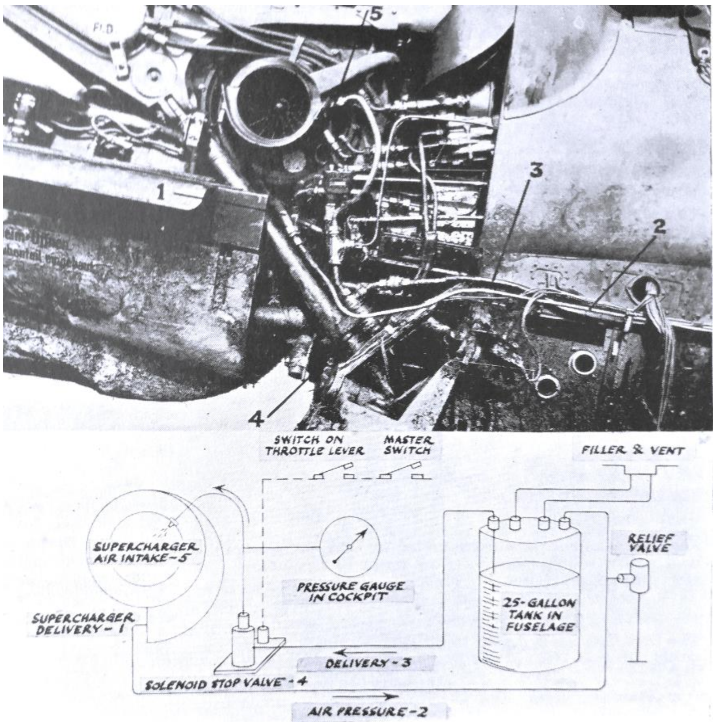

Figure 4. View and diagram of the MW 50 injection system in the Daimler-Benz DB 605 engine in the Messerschmitt BF 109 aircraft (Bridgman, 1970).

Table 1. The influence of MW 50 injection on the power of the Daimler-Benz DB 603L engine and the maximum speed of the Focke-Wulf Ta 152B aircraft powered by it (based on table from *Jane's all the world's aircraft 1945, collector's edition* by Bridgman (1994)).

Engine type	Ceiling [m]	Power [hp]	Power with MW 50 [hp]	Airplane speed [km/h]	Speed with MW 50 [km/h]
DB 603L	0	1,800	2,100	546	578
DB 603L	11,300	-	-	706	-
DB 603L	10,500	-	-	-	745
DB 603L	9,000	1,450	1,750	-	-
DB 603E	0	1,800	2,250	550	595
DB 603E	8,200	-	-	671	-
DB 603E	6,800	-	-	-	698
DB 603E	5,500	1,630	1,900	-	-

This allowed for a significant increase in engine power at low and medium altitudes (Fig. 5). Alternatively, in systems adapted to inject water with methanol, it was possible to use water with ethanol (49.5% water, 50% ethanol, 0.5% anti-corrosion agent) (Bridgman, 1945). In some American engines, such as the Allison V-1710 and at the end of the war also in British ones, water injection was replaced with water-methanol injection, just like in German engines (Lumsden, 1994; Connors, 2010).

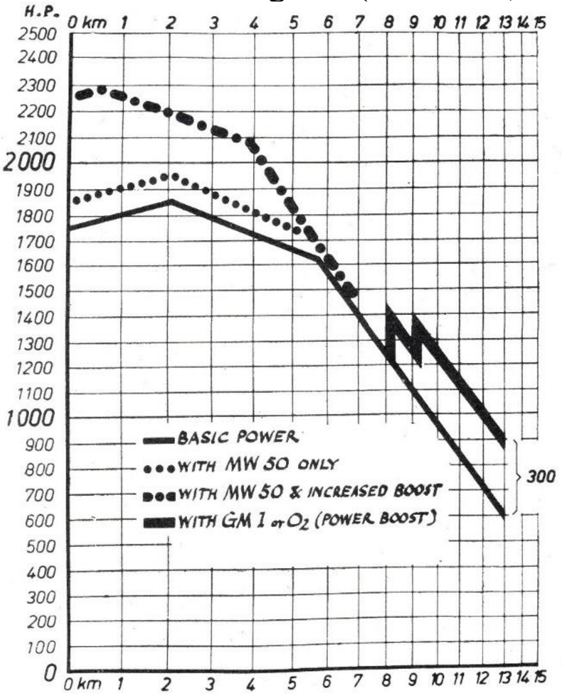

Figure 5. Altitude characteristics of an example German engine without injection, with MW 50 injection, with MW 50 injection and increased charging pressure, and with GM 1 or pure oxygen injection (Bridgman, 1970).

Some versions of the Daimler-Benz DB 601, Junkers Jumo 213 and BMW 801 engines use nitrous-oxide injection. The official name of this system is "ha-ha" or "laughing gas". The designation is GM 1. The gas injected under high pressure was in the form of a liquid, which then evaporated in the charge air. In addition to its cooling properties, nitrous-oxide acted as an oxidizer, which allowed for a higher oxygen content in the cylinder during combustion and meant an increase in engine power at high altitudes (Fig. 5) (Bridgman, 1970).

The BMW 801D engine uses gasoline injection into the charge air. By evaporating, it also allowed the charging air to cool. With the increase in the charging pressure, this allowed for an increase in the maximum power from 1730 hp (1272 kW) to 1870 hp (1375 kW) (Bridgman, 1996).

Unconventional Charging Systems.

The last method of charging aircraft engines introduced into operation was created at the turn of the 1930s and 1940s. It involved recovering power from exhaust gases by the turbine and transmitting it to the crankshaft. Such a solution is referred to as a turbo-compound. The system usually worked with a mechanical supercharger, but there were also engines that were also equipped with a turbocharger. For the first time, such a supercharging method was used in the Rolls-Royce Crecy (Nahum, Foster-Pegg, & Birch, 2013). It was a two-stroke engine in an in-line system (Rubbra, 1990). Many consider it to be the peak example of the development of piston aircraft propulsion (Pełczyński, 2023b).

The most famous engine with such solution is probably the Wright Turbo-Cyclone R-3350, which was equipped with a two-speed mechanically driven centrifugal supercharger. In addition, three turbines were connected via a gear to a shaft to which they transmitted the recovered power. Turbo-Cyclone engines were used in the recent large piston engine-powered passenger aircraft, such as the Douglas DC-7 and the Lokheed Super Constellation (Taylor, 1971). The second well-known example is the Pratt and Whitney R-4360 in a four-row radial system, which turned out to be even better than the aforementioned Wright engines. In some versions it was equipped with a turbo-compound, turbocharger and mechanical supercharger (Connors, 2010). It became the power plant for large military aircraft such as the Convair B-36 Peacemaker bomber.

An interesting engine exploiting the described solution was also the British two-stroke, self-ignition Napier Nomad (Gunston, 1998). The engine, although very interesting, was not a success due to the growing popularity of turbine engines, with which it could no longer compete.

A properly designed engine exhaust system allows exhaust gases to be directed rearward in order to obtain additional thrust. An example would be the Rolls-Royce Merlin, in which it was possible to increase the thrust of the propulsion system by approximately 670 N. Estimated for such a system, during a flight at a speed of approximately 480 km/h, one pound of force, i.e. 4.45 N, is equivalent to additional

1 hp in the engine, assuming a propeller efficiency of 80%. This means that the obtained thrust corresponds to a power of approximately 188 hp (Nahum, Foster-Pegg, & Birch, 2013). At the end of World War II, Rolls-Royce conducted research on developing the concept of using exhaust gases to create additional thrust. According to the first, simplest version, the exhaust gases were to go into a channel through which air flowed. The exhaust gases increased the mass flow in the channel and their energy. Thanks to this, a certain thrust was created. There were several versions of this solution, designed as a straight channel or additionally connected to a mechanical supercharger or turbocharger. A further development was the afterburning of exhaust gases in the channel, which would additionally increase thrust (Nahum, Foster-Pegg, & Birch, 2013).

The solution was provided for the Rolls-Royce Crecy engine. In 1942, a project was created to use it in the Supermarine Spitfire airplane. According to calculations, taking into account the thrust of the exhaust gas, the maximum speed would be 792 km/h. The airplane with the Rolls-Royce Griffon engine produced at that time was able to reach 665 km/h (later versions with the Griffon engine reached approximately 730 km/h) (Nahum, Foster-Pegg, & Birch, 2013).

In 1943, the concept of using Crecy engines in the De Havilland Mosquito aircraft was also created. Ultimately, it turned out that it was impossible to use the full capabilities of the engine in both the Spitfire and Mosquito airplane due to the risk of easily exceeding the maximum permissible speed. For this reason, the decision was made to use the Crecy engine in the more durable airframe of the North America P-51 Mustang airplane. According to calculations, it could achieve a maximum speed of approximately 965 km/h (Nahum, Foster-Pegg, & Birch, 2013).

Similar research has been carried out by Pratt and Whitney since 1946 in the R-4360 engine. The exhaust gases coming out of the cylinders powered an additional turbojet engine. Through channels from the exhaust valves, exhaust gases moved to the combustion chamber, into which fresh air, compressed with a separate compressor, entered. Behind the combustion chamber there was a turbine that powered the jet engine's supercharger and transferred some of the energy to the piston engine's crankshaft. Exhaust gases from the turbojet engine provided additional thrust (Connors, 2010)

Current Development of Supercharging of Piston Aircraft Engines.

Currently, most piston aircraft engines are not designed for high-altitude flights above 4,000 meters. For this reason, a significant part of currently produced aircraft engines are not equipped with superchargers. There is a tendency to use supercharging to ensure the highest possible pressure at sea level, which is intended to improve engine performance, among others, during takeoff (Walentynowicz, 2011).

Increasingly frequent use of direct fuel injection (Walentynowicz, 2021) allows for greater charging pressure at low altitudes. The reason is the lower risk of knocking combustion. In recent times, it has been possible to notice the abandonment of mechanically driven superchargers to turbochargers. Mechanical superchargers are still produced for older engine types and a few new ones. Therefore, their use is becoming less frequent.

Due to the currently slower development of aircraft piston engines than automotive engines, it will be more and more common to encounter the transfer of certain solutions typical of automotive drives to aircraft engines (Pełczyński, 2025).

Conclusions.

At the beginning of the 20th century, in order for airplanes to fly at higher and increasing altitudes, it became a problem to develop an appropriate propulsion system that would allow maintaining adequate power within the required altitude range. Three methods have been developed to achieve this. The first, historic method, is to design an engine designed to operate in the air density prevailing at the assumed altitude. This solution is described primarily in source materials from before World War II (Sherbondy & Wardrop, 1920) The second one is to ensure proper height adjustment of the carburetor, which allows to maintain an appropriate excess air ratio. The third, most effective way is to ensure the highest possible mass of air entering the engine cylinders, despite the decreasing air density with the flight altitude. This is accomplished using superchargers.

Turbochargers were the first to appear in aviation. They allow to maintain the most constant altitude characteristics. In addition, their efficiency increases with height. Initially, the main problem was the resistance of the materials used to the exhaust gas temperature (Pełczyński, 2023b).

Mechanically driven superchargers in aviation initially became much more popular than turbochargers. These were almost exclusively flow superchargers. It was easier to build a gearbox for a mechanical flow supercharger than for a sufficiently durable turbine. It is much more difficult to obtain achieve pressure with a mechanical supercharger over the widest possible range of altitudes. For this reason, complex two-speed or two-stage systems were used. Moreover, the efficiency of the mechanical supercharger decreases with increasing flight altitude. Since World War II, there has been a slow process of abandoning mechanical superchargers in favor of turbochargers.

From the second half of the 1940s and 1950s, piston aircraft engines were replaced by turbine engines in most of their applications (Opara, 2006). For this reason, most aircraft piston engines are currently designed for flights at low altitudes of up to 3,000–4,000 meters and therefore only some of them are supercharged. These are usually turbochargers or mechanical superchargers in older types of engines still in production (Smith, 1986). An example is the Asz-62IR engine, which is a licensed version of the Wright R-1820 engine from 1931. It is currently produced by WSK “PZL-Kalisz” (Kotelnikov, 2005).

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Conflicts of interest.
The authors declare no conflict of interest.

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Огляд історії розвитку систем наддуву поршневих авіаційних двигунів

Анотація. *Предметом статті є огляд найважливіших фактів з історії розвитку систем наддуву поршневих авіаційних двигунів – від зародження авіації до сьогодення, з особливим акцентом на період домінування поршневих двигунів в авіації, тобто першу половину XX століття. У роботі зосереджено увагу на конструктивних рішеннях, які були розроблені протягом років і мали безпосередній вплив на експлуатаційні показники двигунів, висотні характеристики, а отже, й на льотно-технічні характеристики літаків. У перших розділах також висвітлюються причини використання наддуву в авіації, що випливають з несприятливих висотних характеристик атмосферних двигунів, двигунів малої висоти або двигунів, оснащених простими системами не висотного наддуву. Метою статті є всебічне окреслення теми наддуву поршневих авіаційних двигунів, включаючи не лише історію розвитку, а й перспективи цієї технології. Публікацію підготовлено на основі літератури, а передусім – на основі зібраного джерельного матеріалу, такого як каталоги, архівні публікації та каталогові бази даних. Вони дозволяють не лише ознайомитися із реалізованими рішеннями, але й оцінити та проаналізувати їх* *вплив на функціональність двигуна. Знання висотних характеристик чи експлуатаційних показників двигуна дає змогу оцінити доцільність впроваджених конструктивних рішень у його системі наддуву. Подібна робота вимагає не лише історичних досліджень, що спираються на джерела, а й технічних знань інженера, здатного інтерпретувати конкретні тенденції розвитку конструкцій машин, зокрема двигунів, та їх вплив на експлуатаційні показники. Такий підхід дозволяє не лише описати минуле, а й виявити тенденції розвитку протягом років. Аналіз історичних конструкцій і експлуатаційних показників часто ігнорується в науці, оскільки вимагає роботи на стику двох дисциплін – технічної та історичної. Проте він є важливим для розвитку історії техніки, оскільки стосується її центрального об'єкта – технічних засобів.*

Ключові слова: *системи наддуву; поршневі авіаційні двигуни; висотна характеристика; історія двигунів*

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Automotive engine innovation in Francoist Spain through the *Sociedad de Técnicos de Automoción* (STA), 1949–1974

Abstract. *In Spain, there is a lack of historical-sociological approaches to the professional association of engineers of all kinds in general, and automotive engineers in particular, due to the absence of any academic trend or school interested in the study of professions. For this reason, the purpose of this article is to examine the technological changes and development of automobile engines manufactured in Spain during the Francoist regime, based on the innovations of professionals working in the Spanish automotive industry explained by themselves. Our research is grounded in a theoretical framework stated by Cultural History and its reflections on collective imaginations, understood as a mental or conscious frame that can be studied by researchers, to the extent that they are shared by members of any kind of human group as an identity issue: in our case, the Spanish automotive engineers. In addition, the chosen methodology is the study of historical scientific press, where the review of 32 articles written by engineers for the journal Revista de la STA and published by the Sociedad de Técnicos de Automoción between 1949 and 1974, provides a glimpse of these people's collective imagination as they describe their inventions and the entire procedure to achieve them, bringing to light successful discoveries, problems, ill-fated attempts and concerns of all kinds. During the years of Francoist autarky, automotive engineers grappled with the great challenge of overcoming financial adversity and scarce resources to physically produce their innovations in engines, whereas during the developmentalist period, which enjoyed better socio-economic conditions following the Economic Stabilisation Plan of 1959, they undertook new experiments to produce increasingly sophisticated innovations. In its own way, automotive engineers' work was therefore essential in promoting economic growth in Francoist Spain, leaving behind the poverty of the 1940s and 1950s for the consumer society of the 1960s and 1970s. Ultimately, the article concludes how the Revista de la STA, employed as an historical primary source throughout the research, demonstrated its complete preference for innovations promoted by engineers related to automotive state-owned companies, leaving aside those ones from private companies.*

Keywords: *automobile; engineering; technology; innovations; Francoism; Spanish engineers*

Introduction.

The autarkic experiment initiated by the Francoist dictatorship in Spain from 1939 on plunged the economy into an unsustainable situation characterised by poverty, famine, shortages of raw materials, international isolation and more (Richards, 1999; Del Arco Blanco, 2006). While autarky and state interventionism would continue to be presented as indispensable principles to sustain a mirage of national wellbeing and alleged economic independence in the 1950s, several changes in economic policy gradually led to economic —but by no means political— liberalisation that was firmly established by the 1960s (Mayayo, Lo Cascio, & Rúa, 2011, p. 73).

Those years witnessed a new movement called developmentalism, which triggered an industrial, technological and social transformation that the historians and political scientists Guy Hermet (1977), Fernando Heredia (1997), Antonio Cañellas (2006), Sebastian Balfour (2012) and Anna Catharina Hofmann (2023) have described as the authoritarian modernisation of Francoism. Specifically, the turning point came in 1959 with the implementation of the Economic Stabilisation Plan, which launched a few years of accelerated economic expansion that would change the structure of society and modernise Spain (Payne & Palacios, 2014, p. 391; Risques, 2015, pp. 182–183).

While the trade deficit, the rate of inflation and the budget deficit had increased excessively since 1950 (Maluquer de Motes, 2014, p. 258), the opposite started to happen in 1960: the trade balance recorded a surplus, inflation stopped and the budget deficit vanished, enabling the country's incipient incorporation into the dynamics of the Western consumer society and overcoming the fallout of the autarkic disaster (Risques, 2015, pp. 182–183), to such an extent that historians describe the period from 1960 to 1973 as an economic miracle (Maluquer de Motes, 2014, p. 293),[1] promoted by the indicative planning of the three Development Plans: 1964–1967, 1968–1971 and 1972–1975 (Zaratiegui, 2019, p. 489).

Eager for legitimacy, the dictatorship gave credit to Francisco Franco's genius and skill, which was refutable since he personally was solely interested in autarky and demonstrated little common sense and even naïve credulity in applying it (Preston, 2017, p. 741). Indeed, the true developmentalist impulse only came from the technocratic government formed in 1957 with ministers attached to Opus Dei like Laureà López Rodó, Mariano Navarro Rubio and Alberto Ullastres Calvo, who, charged with designing a new economic policy, chose to liberalise Francoist Spain and integrate it into the international capitalist system (Preston, 2017, p. 742; Payne & Palacios, 2014, pp. 437–438).

[1] Other authors delimit the period of the economic miracle between 1962 and 1973, the eleven years of the highest growth in Spanish history with a 7% annual GDP (Mayayo, Lo Cascio, & Rúa, 2011, pp. 120–125).

Spanish economic growth during Francoism occurred in a context of exceptional prosperity in the Western world, the golden age of capitalism that Eric J. Hobsbawm (1995, p. 261) places between 1945 and 1973, from the end of World War II to the first oil crisis. The development therefore established new guidelines for behaviour and consumption that changed all areas of personal, family and collective life in Spanish society (Risques, 2015, pp. 172–173), the most significant being the increase in mobility and independence provided by the automobile, a symbol of social modernisation, as a means of private transport (Maluquer de Motes, 2014, p. 307).

Several academic studies analyse the impact and transformation brought by automobiles to societies all over the world. The first one ever published, by John C. Burnham (1961), speaks of the concept of automobility. Works with a worldwide approach include Steven Parissien's *The Life of the Automobile* (2014), covering the history of the automobile from 1885 and the first motorcar to the present, and two studies by Gijs Mom (2015; 2020) focused on the Atlantic dimension of automobiles first and on their completely global expansion later, giving way to a modern automotive culture throughout the 20th century that remains active today. Furthermore, there are quite a few national perspectives, such as, for example among many others, those by John B. Rae (1965), James J. Flink (1976), Michael L. Berger (2001), Tom McCarthy (2007) and John A. Heitmann (2009) for the United States; Harold J. Perkin (2016) for the United Kingdom; David Inglis (2004) and Éamon Ó Cofaigh (2022) for France; Rolf Spilker (2012) and Bernhard Rieger (2013) for Germany; Jonathan R. Zatlin (1997), Lewis H. Siegelbaum (2011) and Luminita Gatejel (2017) for former USSR republics and other Soviet satellite countries; and Ricard Rosich for Spain itself (2022a; 2022b; 2023).

In Francoist Spain, the automobile certainly brought about industrial, technological and social transformations characteristic of the new developmentalist economic dynamic. In this context, there was an expansion of automobiles at relatively affordable prices for a considerable mass of people, though still not the majority, considering that the number of automobiles manufactured soared from 637 in 1950 to 1,140,776 in 1978 (Ortiz-Villajos, 2010, p. 138, 151), with socio-cultural data showing a rise from 4% of households with an automobile in 1960, one vehicle for every fifty-five inhabitants, to 35% in 1971 and 46% in 1974, one vehicle for every nine inhabitants (Cazorla, 2016, pp. 260–261; De Riquer, 2010, p. 657).

From the triple industrial, technological and social transformation that led to the expansion of the automobile in Francoist Spain, this article aims to investigate its involvement in technological change, highlighting the development of automotive engineering from the years of autarky to those of developmentalism and approaching the collective imagination of professionals in the automotive industry. In fact, this people achieved their expansionist objectives and turned into a new social elite alongside, whilst providing society with innovations in favour of more and better automobiles to be driven, contributing through their modernisation to the political survival of the Francoist regime. This supports Lino Camprubí's thesis (2014) attributing a social and political role to all kinds of Spanish engineers in the configuration of the country during both the periods of autarky and developmentalism under Francoism by using technology as the key for modernisation towards Spaniards' progress and thereby propping up the dictatorship itself.

Research Methods.

This article concerns about the lack of historical-sociological approaches to the professional association of engineers in Spain, which Darina Martykánová (2021, p. 310) has attributed to the absence of any academic trend or school interested in studying the professions in Spain. In order to place a contribution in this area, we propose the Spanish automotive engineers' case of study during Francoism, taking attention on a chronology when several innovations were made and Spanish society started its motorization process. Our interest is focused on all those technological experiments and reflections explained personally by the key figures in this history, that is, the Spanish automotive engineers themselves. This approach considers academic theories from Cultural History field of study, which explores how reality takes part in the construction of collective representations in human experience (Chartier, 1992, p. IV). Thus, the research engages with the concept of collective imagination: mental or conscious frameworks shared by groups, communities or societies that possess an identity issue in common (Burke, 2006, pp. 83–85).

Our qualitative methodology seeks to document the technological innovations embedded in the collective imagination of Spanish automotive engineers during the Francoist era. In order to uncover their contributions to the modernisation of the country, this article adopts a case study approach centred exclusively on innovations made in automobile engines. We use as a historical source the review of 32 articles written by automotive engineers for a periodical publication called *Revista de la STA*, which was issued by the *Sociedad de Técnicos de Automoción* (STA), a private institution in charge of overseeing progress in automobile technology by bringing together under its philosophy the professionals ready to make it possible. The article spans the period from 1949 (autarky), when both the STA and the *Revista de la STA* were founded, to 1974 (developmentalism), when the journal published its last issues before stopping temporarily for one year. The body of the article is structured in four main sections: 1) the importance and contributions of the STA to Spanish automotive engineering; 2) the significance of experiments with diesel engines to motorise a country in great need of improvement in the transport of goods and passengers by road (trucks, taxis and buses); and mechanical innovations applied to both diesel and petrol engines, highlighting 3) the internal combustion process on the one hand and 4) the lubrication process on the other.

Results.

1. The STA: inception, essence and domestic and international projection.

The STA (see Figure 1), which still exists today, was created on 24 February 1949 during the assembly of an organising committee made up of automotive engineers from

Spain at the time, residing in Barcelona, who worked together to create an associative organisation that looked after collective benefits with the technological advancement of an industry that was being (re)built after the destructive Spanish Civil War and its following backwardness.[2] The new association was established in the premises lent by the *Asociación Técnica Española de Estudios Metalúrgicos* (ATEEM), which had existed since 1943 (ATEEM, 1946, p. 55), and its registered office was also in Barcelona. It could only see the light of day after the chair of the organising committee, Ramón Durán, obtained authorisation from the sub-secretariat of the Ministry of the Interior, and during the founding act the minutes state that it was created for the ultimate purpose of "putting automotive technology in our country where it belongs".[3] The STA was managed by two boards: the supervisory board, formed by Wifredo P. Ricart as chair and by board members Andrés Barcala, Julio Rentería, Manuel Junoy, Mariano Fernández de Córdoba and Sebastián Nadal; and the managing board, composed of Wifredo P. Ricart as chair, with Miguel Guinea as first deputy chair, Miguel Elizalde as second deputy chair, Carlos Coll as secretary, Manuel Serdá Torelló as vice-secretary, Manuel Torrado as treasurer, Ramón Durán as accountant and voting members Carlos María Carreras Rius, Fernando Medialdea, Juan Miralles de Imperial and Andrés Montaner.[4]

Figure 1. Logotype of the *Sociedad de Técnicos de Automoción* (STA, wo/d).

The Article 4, letter d) of the founding statutes explained the initiative "to promote congresses and periodic meetings to publicise and discuss the information received or other topics of interest for the purposes of the Association and to attend international congresses and meetings with the same ends".[5] This goal was particularly important due to the web of alliances and transnational connections weaved between the Spanish automotive engineers associated with the STA and their foreign European, Anglo-Saxon and even Japanese counterparts, flowing with exchanges of ideas that were mutually enriching and especially valuable for the professionals of the STA, who not

[2] STA Editorial Team (1949). Actividades sociales. Constitución de la S.T.A. en la asamblea de 24 febrero, 1949. *Revista de la STA*, I (1), 75 [in Spanish].
[3] Ibid.
[4] Ibid.
[5] Archive of the Sociedad de Técnicos de Automoción (ASTA). *Sociedad de Técnicos de Automoción (S.T.A.). Estatutos*, wo/d, wo/b [in Spanish].

only were pleasantly interested in finding out what was being invented on the other side of the Pyrenees, the Atlantic and the Pacific, but they also wanted to share their own studies with the rest of the world.

We cannot understand this eagerness and determination without knowing Spain's historical importance before the Civil War as a world-class benchmark in automobile manufacturing during the first third of the 20th century, with Barcelona as the cradle of the engine and the launch of various small and medium-sized initiatives such as Elizalde, but also brands with greater global impact like Hispano-Suiza and Ford. Due to their historical awareness of their predecessors, the founding members of the STA unsurprisingly decided to appoint several honorary members. These included international automotive engineering authorities like France's Maurice Norroy and the United Kingdom's Harry R. Ricardo, clearly for their critical contributions, but also figures of the Spanish automotive industry such as Switzerland's Marc Birkigt, who had co-founded the now-defunct company Hispano-Suiza with Spain's Damià Mateu and Francesc Seix in 1904, and Carmen Badía, the widow of Arturo Elizalde, who had continued to run the company Elizalde (founded in 1908) since her husband's death in 1925, even though it focused on aviation engines and no longer on automobiles at that time.[6]

Despite autarkic Spain's international isolation, the STA expressed its desire to connect associated technicians with their European counterparts in the first steps it took as an institution. During the first meeting of the supervisory and management boards on 3 March 1949, the chair of both boards, Wifredo P. Ricart, proposed to incorporate the STA into the *Féderation Internationale des Sociétés d'Ingenieurs des Techniques de l'Automobile* (FISITA), based in Paris, with an alternating presidency that would begin with Maurice Norroy and later pass on to other figures, including Ricart himself between 1957 and 1959. Created in 1948, the FISITA still exists today (see Figure 2). Ricart's motion was approved unanimously. As explained during the session in question, the FISITA served as an umbrella for different automotive engineering associations equivalent to the STA that had been created in different countries and with which it was interested in maintaining close intellectual contact.

These associations included the French *Societé d'Ingenieurs de l'Automobile* (SIA), the Italian *Associazione Tecnica dell'Automobile* (ATA), the Franco-Polish *Societé d'Ingenieurs Téchniques Polonais – Française* (SITF) and the *Swiss Schweizerischen Auto Techniker-Verband* (SATV).[7] With the addition of the STA, we can see that the FISITA had five members from its early days in the late 1940s, though the number of federated automotive engineering associations would grow in the years to come and reach a total of fourteen members by its 25th anniversary in 1972, with the anticipation of achieving twenty members shortly thereafter, following the

[6] ASTA. *Primera Sesión de las Juntas Superior y Directiva de la S.T.A., del 3 marzo 1949*, wo/d, wo/b [in Spanish]; ASTA. *Sesión de las juntas superior y directiva del 4 marzo 1949*, wo/d, wo/b [in Spanish].

[7] STA Editorial Team (1950). La reunión de F.I.S.I.T.A. del día 10 de octubre de 1949. *Revista de la STA*, II (3), 90–91 [in Spanish].

momentous incorporations of the *British Institution of Mechanical Engineers – Automobile Division* (IMechE-AD), the *German Verband Der Automobilindustrie* (VDA), the *Belgian Societé Belge d'Ingenieurs de l'Automobile* (SBIA), the *American Society of Automotive Engineers* (SAE), the *Japan Society of Automotive Engineers* (JSAE) and the *Society of Automotive Engineers – Australasia* (SAE-A); in 1972, it was also estimated that around 25,000 engineers were part of FISITA.[8]

Figure 2. Logotype of the *Féderation Internationale des Sociétés d'Ingenieurs des Techniques de l'Automobile* (FISITA, wo/d).

The main outcome of the interrelationships and transnational links maintained between these federated automotive engineering associations was the *FISITA World Automotive Congress*, held once every two years until the present day in different places around the world.[9] Simultaneously, each of the FISITA member associations, spread over different countries around the world, would also participate separately and outside the federal body in different editions of an international congress that dealt specifically with internal combustion engines, the *Congrès International des Moteurs/Machines à Combustion Interne* (CIMAC), which also is still held today biennially or triennially in different places around the world (Fleishhack & Russak, 2001).

Alongside all the congresses in which the STA would participate, there was another showcase for its scientific and technical dynamism, the aforementioned periodical publication *Revista de la STA*. This technical journal would serve as an essential megaphone for Spanish automotive innovation that disregarded national borders and spread throughout the world via a web of federated relations woven by the FISITA. It was a primary objective of the STA from the start; indeed, its creation was planned in the founding statutes' section on means of action, specifically in Article 5,

[8] STA Editorial Team (1972). FISITA = 25 Años. *Revista de la STA*, XXIV (94), 78–79 [in Spanish].

[9] An almost complete chronology with geographical locations of the editions of the congress in question can be found at: Japan Society of Automotive Engineers (JSAE). *Venues*. FISITA World Automotive Congress [online]. Date of check: 28 February, 2023. Available at: https://www.jsae.or.jp/en/int_rel/fisita.php

letter a): "Publication of a technical automotive journal, whenever possible, which will be sent to each of the associates".[10]

Once that was established, the first issue of the journal was published in June 1949.[11] Future issues would be published quarterly until 1974, when the one hundredth issue was released.[12] However, the STA published no issues in 1975 due to a budgetary deficit.[13] It resumed publishing in 1976 with a smaller format and irregular periodicity, while trying to cope with the high printing costs that a journal of such magnitudes entailed. This continued until 2013, when the last issue was published. Certainly, the journal aroused the interest of foreign automotive engineers who wished to publish their studies there to share them and exchange innovative knowledge with their Spanish counterparts, but above all a considerable majority of its scientific and technical articles were written by Spanish automotive engineers working for the benefit of collective technological progress in Spain.

2. A demiurge for the developmentalist automotive industry: the diesel engine.

After the tragic use of producer gas to run automobiles in the years immediately after the Spanish Civil War (Preston, 2019, p. 369), there was great concern about abandoning its precarious use to turn to fossil fuels like the other Western countries. Faced with a shortage of raw materials determined by the Francoist dictatorship's authoritarian nature and consequent international isolation, with an oil embargo in force (Maluquer de Motes, 2014, p. 199; Caruana, 2009, p. 25, 32), the most attractive option for business was to invest in diesel engines, as they were more fuel-efficient than those of the petrol system and would better optimise the dosed amount of oil that arrived in Spain during the toughest period of autarky in the 1940s. This innovation came to stay.

It is true that the timid economic liberalisation of the 1950s would allow attention to shift back to petrol engines as a result of a better supply of larger amounts of essential resources.[14] Moreover, the automobiles that proliferated intensely in the streets of developmentalist Spain in the 1960s and 1970s were powered by both petrol and diesel engines in roughly balanced measure. Nevertheless, it is worthwhile to study the impact of diesel engines specifically as the first great innovation that would mark the beginning of domestic automotive development in the wake of the interruptions caused by the Spanish Civil War, focusing especially on serving industrial vehicles (like trucks) and passenger cars (like cabs or buses) that were used day in and day out for work by transporters, while also impacting the rest of the automobile users to build something that could be called diesel culture, which would surely continue during the

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[10] ASTA. *Sociedad de Técnicos de Automoción (S.T.A.). Estatutos*, wo/d, wo/b [in Spanish].
[11] *Revista de la STA*, I (1), 1949 [in Spanish].
[12] *Revista de la STA*, XXVI (100), 1974 [in Spanish].
[13] STA Editorial Team (1976). Editorial. *Revista de la STA*, XXVIII (101), 9 [in Spanish].
[14] A clear example of this is the emblematic SEAT 600 (1957–1973), which always had an inline 4-cylinder engine fuelled with petrol. See: Martín, 2022, pp. 42–61.

intense motorisation of the late Francoism, the following decades and even into the 21st century.

That is, whilst Spanish-made trucks and buses were primarily factory-equipped with diesel engines, many taxi drivers, but even private users in general, gradually became interested in transforming their original petrol-powered utilitarian vehicles into diesel-powered ones thanks to mechanic workshops that could install English-made Perkins diesel engines or cheaper and equally efficient Spanish-made Barreiros diesel engines (García Ruiz & Santos Redondo, 2003, p. 73, 75, 77–78, & 83). This successful implementation of a diesel culture in Spain reflects some similarities with the situation of other European countries, like Germany, where Volkswagen and Mercedes-Benz's diesel engines became more popular between the 1960s and 1980s by achieving low fuel consumption together with good performance and good driveability; yet it differs totally from what happened in the United States in the same period of time, as General Motors' diesel engines offered low reliability, and as a result, American customers had very negative perceptions of all diesel engines, regardless of the manufacturer (Neumaier, 2010, pp. 123–126 & 136–137).

As Spanish technician Adrián Fonollosa Rodríguez explained in the opening lesson of the 1971–1972 Advanced Automotive Course organised by the STA, the diesel engine works in such a way that an injector obtains the diesel fuel via a pump and sends it into the combustion chamber of the cylinders, where it is ignited by some heated parts. When the pistons slide up, the air is compressed and heated at a much higher ratio than petrol engines operating with spark plugs. This results in less fuel use each time the fuel ignition process is repeated while the engine is running.[15]

Pegaso trucks and buses were subjects of the pioneering research in diesel engines carried out in Spain since the creation of the *Empresa Nacional de Autocamiones, S. A.* (ENASA) in 1946, in the midst of the autarkic economy. Aimed at producing its own technology and achieving independence from external supplies, ENASA was driven by the talent of professionals who were part of the *Centro de Estudios Técnicos de Automoción* (CETA), created that same year. Their mutual cooperation involved CETA acting as an automotive laboratory for planning and research-based experiments whose results it shared with ENASA at the time or later. Apart from the designers and engineers on ENASA's team, who were usually affiliated with CETA at the same time, it was also formed by a workforce trained for industrial manufacturing and production (González et al., 2013, p. 439; Nadal, 2019, p. 290).

Both companies, whose mission was to promote automotive industrialisation, were created by Juan Antonio Suanzes as president of the Spanish government's *Instituto Nacional de Industria* (INI), a public institution in the image and likeness of the fascist Italian *Instituto per la Ricostruzione Industriale*. It was founded in 1941 to ensure state supervision and intervention in several industrial projects with substantial

[15] Fonollosa García, A. (1972). Inyección en el motor diésel. *Revista de la STA*, XXIV (93), 38–44 [in Spanish].

financial investment (San Román, 1995, p. 142; De Corso, 2015).[16] This is where Wifredo P. Ricart entered the scene (see Figure 3). An industrial engineer who had acquired extensive knowledge at the Italian firm Alfa Romeo, Ricart was working with a group of people that included specialists from the Barcelona-based manufacturers Eucort and Elizalde (Catalan, 2017, p. 91; Catalan, 2000, p. 124; Nadal, 2019, pp. 288–289). As such, the INI chose him between 1945 and 1946 as the ideal person to be entrusted with managing the leading both ENASA and CETA (Lage, 1992, p. 119).

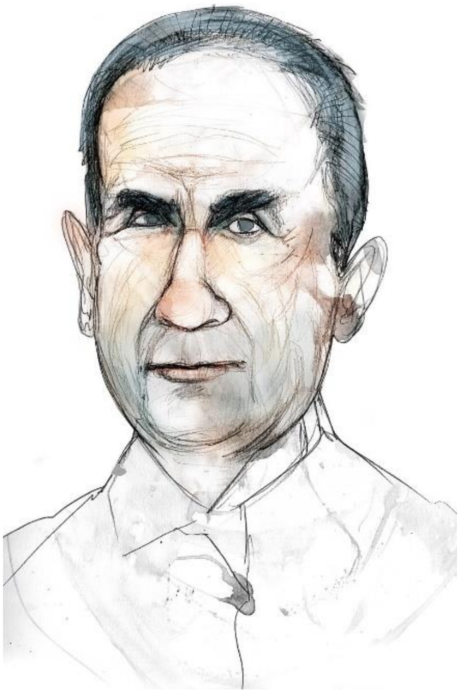

Figure 3. Portrait of Wifredo P. Ricart (Merle, 2011).

To be precise, ENASA was built over the ruins of the legendary company Hispano-Suiza, which had been in decline since the Second Republic and was unable to sell its luxury cars after the Spanish Civil War: as soon as it was forced to cease operations, the INI, which had never done anything to help it to survive, took advantage of its fall to buy the La Sagrera factory (see Figure 4), thereby capturing its technical and infrastructural capital for ENASA (Nadal, 2019, pp. 295–296; Catalan, 2017, p. 92; Catalan, 2000, p. 124). ENASA inherited from Hispano-Suiza a diesel engine prototype devised in 1946 by engineers Marc Birkigt and Louis Birkigt called 66D (Lage, 1992, pp. 111 & 142–145), which it presented as the ideal basis for building the heavy vehicles that it was charged to produce (Nadal, 2019, pp. 287–288). These heavy

[16] Ley de 25 de septiembre de 1941 por la que se crea el Instituto Nacional de Industria. *Boletín Oficial del Estado (BOE)*, 273, 30 September 1941, 7516–7519 [in Spanish].

vehicles were considered necessary for boosting the sluggish economic activity in Spain under the terms laid out in the National Motorisation Plan of 1940.[17]

Figure 4. Old Hispano-Suiza's factory in La Sagrera, Barcelona (Hispano-Suiza, wo/d).

Considered a towering figure in the business world and one of the fathers of the Spanish automotive industry during the Francoist era, Wifredo P. Ricart is also remembered for having been the president and a founding member of the STA itself. In early 1950, he was already well aware of the ever-increasing supremacy of diesel technology, particularly in the field of utility trucks for transporting goods and people, saying:

> *"The development of industrial transport by road in all countries [...] is creating major problems from a technical and constructive point of view. The competition demands a continuous drop in the cost per useful tonne-kilometre. [...] For vehicles with over eight tonnes of total cargo weight, on the ground, we find that the diesel engine is used almost exclusively for new types of construction in Europe".*[18]

In fact, this is how he justified the significance of his research in later years, which consisted of manufacturing a diesel engine model that offered higher performance to improve driving, gears —while making them more refined— and the relationship between useful weight and tare. To top if off, even if it seems contradictory, he also sought to further reduce fuel consumption specifically. This is how he adapted a torque converter and a turbine to a simple kind of diesel engine: the invention could suck the gases from the exhaust pipe and recirculate them through the mechanical system,

[17] Decreto de 10 de febrero de 1940 dando normas para implantar la fabricación del automóvil. *BOE*, 56, 25 February 1940, 1378-1380 [in Spanish].
[18] Ricart, W. P. (1950). Motores para Vehículos Industriales. *Revista de la STA*, II (3), 13 [in Spanish].

generating energy that sent more air to the engine (supercharging). This improved performance without needing to use more fuel, thereby reducing the global consumption index.[19]

The emergence of this mechanical engineering, designed and manufactured entirely in Spain as a result of the insurmountable cooperation between CETA (Madrid) and ENASA (Barcelona), was inspected at great length in 1950 by the industrial engineer Manuel Serdá Torelló, CETA's head of experiments and chief mechanical engineer, who analysed each component piece by piece, including the cylinder block, crankshaft, pistons, connecting rods, cylinder heads, valve distribution and cams, greasing circuits, cooling equipment, injectors, injection pump, turbines and other accessories that gave it such decisive characteristics. In particular, he was impressed by the "overall lightness of the unit together with great rigidity and robustness of all vital components, direct injection and a special combustion chamber with which a low fuel consumption is obtained, absence of vibration and easy starting".[20]

In the late 1950s, the continuation of the mechanical studies carried out by Wifredo P. Ricart and his team of professionals would result in the appearance of a new engine model intended for maritime use. This may seem surprising because they specialised in trucks, but in the end it is understandable since ENASA had been founded in 1946 to support the Francoist regime's action and intervention in the old Hispano-Suiza company and was called upon to work in general for the "indispensable industrial development of our Nation".[21] That would not be all: demonstrating that there were no limits to the engineering capabilities of CETA and the highly qualified workforce of ENASA, by 1951 a mobile engine would see the light of day, as Manuel Serdá Torelló said, built on a cast iron bench that turned it into a mechanical system expressly designed to run generator sets —like those required by travelling commercial and/or professional activities— or to operate any type of factory machinery.[22] In 1967, Serdá Torelló summarised the many different versions, developments and modifications carried out on the original Pegaso diesel engine from the creation of ENASA in the midst of the autarkic period until the years of developmentalism.[23] By this time, he had been promoted to deputy director of the company's projects and experiments due to this brilliant career within the company, working side by side with Wifredo P. Ricart.

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[19] Ibid., 13-24.

[20] Serdá Torelló, M. (1950). El Motor Pegaso Diésel. *Revista de la STA*, II (3), 25 [in Spanish].

[21] Decreto de 1º de mayo de 1946 sobre creación por el Instituto Nacional de Industria, de una Empresa mixta para la construcción de autocamiones pesados y medios y de motores Diésel. *BOE*, 122, 2 May 1946, 3189–3190 [in Spanish].

[22] Serdá Torelló, M. (1950). El Motor Pegaso Diésel Marino. *Revista de la STA*, II (6), 22–23 [in Spanish]; Serdá Torelló, M. (1951). El Motor Industrial Pegaso Diésel – Instalación Móvil. *Revista de la STA*, III (8), 67–73 [in Spanish].

[23] Serdá Torelló, M. (1965). Evolución de los motores Diésel de 4 tiempos con bloque de aleación ligera para camiones pesados. *Revista de la STA*, XVII (67), 44–49 [in Spanish].

In the automotive professionals' imagination, the oil shortage was still important, as Spain continued to suffer from it just as in the early 1950s, however much their creation of their own diesel engines had been a good step forward in energy savings. Faced with the great obstacle of the lack of elementary raw materials, it seems that the only possible solution was to continue innovating without falling into despair, as revealed in the testimony of Juan Miralles de Imperial, chief engineer of the engine department at *Maquinista Terrestre y Marítima, S. A.* (MTM), when he shared his work in the development of diesel engines that could run on gas with the spectre of the possible depletion of liquid fuel in Spain, focusing on the dual diesel and diesel gas patents that had been released in the USA and in the rest of Europe, respectively.[24]

Another possible way to deal with diesel fuel, which arrived in Spain in very limited amounts and at a very expensive price, was proposed by Juan José de Quixano, an industrial engineer working in MTM's engine department. His alternative featured the waste obtained in diesel refineries after its substance was distilled, given that this waste produced a fuel much more economical than diesel that was called fuel oil.[25]

Throughout the Francoist period, the improvement and perfection of the combustion process of diesel engines remained a subject of great concern for automotive engineers. An early example of this came in 1950 when Manuel Serdá Torelló vindicated the unquestionable importance of properly tuning manufactured diesel engines to guarantee that the combustion process provided the desired results once the customer had taken possession of the vehicle. In his judgment, several conclusive evidences were the key, such as ensuring that the diesel and air be mixed in equal amounts, that the combustion chamber must be shaped to allow an intermediate compression system to perform well at both low and high temperatures and that the injectors and injection pump must be synchronised to act according to whether the engine revs more or less and tows a heavier or lighter load if the use of fuel is to be optimised at all times and not wasted. [26]

A more recent example came in 1972 when Carlos María Carreras Rius, an industrial engineer and technical secretary of ENASA's factory in Barcelona, pointed out the clear differences between petrol and diesel engines, stressing the greater complexity of the latter since it required a constant intake of air, the air and fuel had to mix inside the cylinder and not outside and the mixture had to ignite via thermal compression. Since the diesel engine does not use a carburettor or spark plugs, which petrol engines require to regulate the combustion process, Carreras Rius proposed a method of turbulence in the diesel engine's cylinders that caused the air inside to react

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[24] Miralles de Imperial, J. (1950). La marcha Diésel-Gas. Motores alimentados con combustible líquido o gaseoso indistintamente. *Revista de la STA*, II (5), 75 [in Spanish].

[25] De Quixano, J. J. (1951). Empleo de fuel-oil en los motores Diésel. *Revista de la STA*, III (10), 52–62 [in Spanish].

[26] Serdá Torelló, M. (1950). Puesta a punto de la combustión en los motores Diésel rápidos. *Revista de la STA*, II (4), 61–69 [in Spanish].

uniformly with the incoming fuel, satisfactorily ensuring that "each molecule of fuel finds its corresponding oxygen molecule to guarantee good combustion".[27]

Closely linked to the issue of fuel, automotive professionals also thought about the nature of the power that a diesel engine could generate and the factors that influenced it for better or for worse. Thus, in 1965, José G. Pérez Castillo, an engineer and head of quality control at ENASA in Madrid, theorised that the driving force of a diesel engine was conditioned by an atmospheric factor —depending on whether more or less air entered the cylinders—, due to the state of the fuel —namely, the hotter it got, the more calories were activated in the combustion chamber, boosting performance— and ultimately owing to the engine itself —since the injection pumps had a fuel transfer limit that could not be exceeded, so the power was limited to their maximum performance—.[28] Pérez Castillo revisited the subject again in 1969, setting out to investigate the extent to which atmospheric variations caused by meteorological or geographical changes, as well as variations in the composition of diesel fuel coming from different refineries, could alter engine power and/or the amounts of fuel consumption.[29]

We must also mention a series of small experiments that would willingly help to diesel technology to advance during the Francoist era. In 1951, Ramón Pintó Oliveras, an industrial engineer and professor specialised in thermal engines at the *Escola Especial d'Enginyers Industrials de Barcelona*, pointed out the twofold problem of vehicles that transported people, as bus passengers wanted more comfort based on reducing the noise of fast diesel engines, while their drivers wished for improvements to the accelerator to achieve the smoother experience provided by petrol engines. Pintó Oliveras was frustrated with his experiments using mechanical regulators until he found satisfactory results with the invention of a hydraulic regulator that allowed him to lower the idle speed, and thereby to reduce mechanical noise, with no danger of stalling the engine, while simultaneously providing better power output measurement when stepping on the accelerator. Both goals were achieved because such a hydraulic mechanism always kept the moving parts of the engine in light and lubricated operation.[30] Like many other innovations, this one in particular clearly shows how important it was (and of course still is) for an automotive engineer to relate to drivers and automobile users by establishing a dialectic relationship that, above all, allowed Pintó Oliveras to discover non-technical factors from common people who, as explained, would help him to innovate with satisfactory results for the consumer's

[27] Carreras Rius, C. M. (1972). Combustión en los motores Diésel rápidos. *Revista de la STA*, XXIV (93), 31–37 [in Spanish].
[28] Pérez Castillo, J. G. (1965). Corrección de potencia en los motores «Diésel». *Revista de la STA*, XVII (67), 34–43 [in Spanish].
[29] Pérez Castillo, J. G. (1969). Variación de la potencia de los motores Diésel con las condiciones atmosféricas y de combustible. *Revista de la STA*, XXI (82), 131–145 [in Spanish].
[30] Pintó Oliveras, R. (1951). Regulación hidráulica en motores Diésel rápidos. *Revista de la STA*, III (9), 55–58 [in Spanish].

experience. In fact, researchers like Andreas Knie and Mikael Hård (2000; 2001; 2010) have put into value this kind of technological labour procedure, under the need for engineers not to stop just in the constructive work of their innovations and get in contact with, in terms of historian John M. Staudenmaier (1985), a broad cultural ambience around them to achieve the expected success, by knowing the broader industrial context, regulatory frameworks, user views and interpretations, as well as the cultural integration of a specific technology.

In 1952, José Ramón Ricart (the son of the great Wifredo P. Ricart), an industrial engineer and head of MTM's technical office of diesel engines, set out to solve the classic problems presented by adapting a turbocharger to a diesel engine, thinking that doing so still had merit because if it turned out well, it would possibly provide a way to boost power without having to manipulate the engine's rotation system. With this aim in mind, he explained how to adjust the air flow for the turbocharger, its boost pressure, the exhaust gases, the valve overlap, the injection rates and the amount of water needed.[31]

In 1962, A. Monclús Torá, a chemist working for ENASA in Barcelona, came up with an equally important way to extend the life of diesel engines: unaware of how diesel engine oil, which is fundamental for lubrication, evolved, and since it was impossible for drivers to run tests in laboratories, his technique was to take a sample of used oil and a sample of new oil and to pour drops periodically onto a paper filter so he could compare both pieces of evidence. As the kilometrage progressed, the spot of used oil gradually lost the four colour zones characteristic of new oil and became concentrated in a uniform colour, showing how the various ingredients had lost their properties.[32]

3. Improving the internal combustion process in diesel and petrol engines.

The existence of every combustion engine is justified in a process that takes place in a matter of seconds. This process is called internal combustion, as is commonly the type of engine itself, due to a metonymic urge to take the part for the whole. Various mechanical agents are involved in internal combustion, such as the crankshaft, cylinders, combustion chambers, pistons, connecting rods, cylinder head, intake valves, exhaust valves, injectors and carburettor, all of which participate in burning the fuel that generates driving power for the automobile.

In 1959, Gerardo Soeliger, an engineer working for the *Sociedad Española de Automóviles de Turismo* (SEAT, S. A.) —the state manufacturer of utility automobiles promoted since 1950 by the INI, six Spanish banking institutions and the *Fabbrica Italiana Automobili Torino* (FIAT) (Catalan, 2012, p. 48)—, explained that every

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[31] Ricart, J. R. (1952). Adaptación de la turbosoplante a motores Diésel. *Revista de la STA*, IV (11), 18–29 [in Spanish].

[32] Monclús Torá, A. (1962). El control del aceite de motor en vehículos Diésel. *Revista de la STA*, XIV (55), 46–49 [in Spanish].

internal combustion engine had a four-stage combustion cycle of air and fuel, just like today: the intake, the compression, the expansion caused by spark plugs (petrol engines) or by block heaters (diesel engines), and the expulsion of resulting gases. He also pointed out that all four stages of the process could be fulfilled in a two-stroke or four-stroke system, depending on whether the engine was designed so that the combustion took place in two half-turns of the piston or in four.[33]

While it can be assumed that any mechanical component of a combustion engine is indispensable to the point that any failure in particular impairs the dynamics of the whole, one core piece for its proper operation is the combustion chamber included in each cylinder of an automobile. The masses of air and volumes of fuel that it receives form a potentially reactive mixture that ignited by a spark or by heat when a piston causes compression each time it moves back and forth due to the motion of a connecting rod connected to the crankshaft axis. Due to the complexity of working as the space where ignition takes place after concentrating all the components that are part of it, it is hardly surprising that when the automotive industry resumed after the Spanish Civil War, the combustion chamber was the first part of the combustion engine to attract interest and even concern among automotive technicians.

A clear example of this is the research conducted in 1950 by Juan Miralles de Imperial, the chief engineer of MTM's engine department. Focusing on the diesel engine, as it was presented as crucial for promoting motorisation in Spain, he discovered that the combustion chambers in some models were designed in such a way that they were unable to achieve the most successful performance possible. After running a series of tests, he was able to formulate more efficient proposals. Considering slow and large engines, he noted that the shape of their combustion chambers prevented air from circulating easily. To remedy this, he decided to remove a central mount from the structure and place a peripheral ring there instead, thereby allowing air to circulate faster from the edges toward the centre. Turning his attention to small and fast engines, he identified the smaller space of the combustion chambers as the cause of deposits of particles that had accumulated harmfully after not having had the time or place to burn up and discovered that by designing an orthogonal wall inside it, he could get the accepted fuel to bounce off it and, consequently, allowing those particles' burn up. In both cases studied, Miralles de Imperial took the additional step of causing turbulence in the air to make it circulate even faster, either by installing a valve with a deflector or screen, as designed by Hesselman, or by means of the swirl compression method innovated by the Swiss manufacturing company Saurer.[34] Fourteen years later, in 1964, he would run more tests, generating turbulence to boost the efficiency of high-performance engines, with equally successful results.[35]

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[33] Soeliger, G. (1959). ¿Motores de dos o de cuatro tiempos?. *Revista de la STA*, XI (42), 45–48 [in Spanish].
[34] Miralles de Imperial, J. (1950). Cámaras de combustión. Consideraciones y experiencias. *Revista de la STA*, II (3), 55–59 [in Spanish].
[35] Miralles de Imperial, J. (1964). Turbulencia. *Revista de la STA*, XVI (63), 57–59 [in Spanish].

In an attempt to boost internal combustion engines' power, Carlos María Carreras Rius, an industrial engineer and technical secretary of ENASA's factory in Barcelona, pursued a procedure in 1952 that he described as clean to the extent that it had no negative impact on fuel consumption. While it could be applicable to the trucks manufactured by the company for which he worked, it actually focused on the fast engines of vehicles that might even be prepared to enter in competitions.[36] Though not explicitly acknowledged in his research, this must be considered in context, as at around the same time Wifredo P. Ricart was leading ENASA's creation of the Pegaso Z-102 (1951–1958) (see Figure 5), a sports car with a limited production run of only 84 units that would give rise to some offshoot versions suitable for racing, well beyond the coupé and cabriolet bodies designed for use in the street (Lage, 1992, pp. 161–167). The net increase in power that Carreras Rius advocated was specified in a basic aspect that was nonetheless not always easy to achieve, such as ensuring that any voids in the combustion chamber inside each cylinder were optimally filled by multiple carburettors, at best one for each cylinder, as a way to boost the pressure of air and fuel during their injection into the cylinders and keep both substances there firmly when their mixture was ignited.[37]

Figure 5. Advertisement of the Pegaso Z-102 (Álvarez, 2014).

[36] Carreras Rius, C. M. (1952). Orientaciones para el proyecto de motores rápidos a alimentación atmosférica. *Revista de la STA*, IV (12), 38–46 [in Spanish].
[37] Ibid., 44–45.

As one can see, the issue of carburation, operating exclusively for petrol engines —old diesel engines operated with a set of pre-chamber injectors—, was hardly inconsequential for internal combustion. José Mañas, an industrial engineer and head of experiments at CETA, linked to ENASA, used three different types of carburettors in Spain in 1954. The first was a carburettor with a tube-shaped section for the constant passage of air, which worked by delivering a diameter of fuel passage for each diameter of air passage based on a plate popularly known as a butterfly that acted as a horizontal throttle valve connected to the accelerator pedal cable to control the amount of air entering to combine with the fuel coming from an open container and closed with a valve. The second was a carburettor with a variable airflow section, which had a noticeably different layout: the butterfly was replaced by an intake runner valve that opened and closed on a large airflow rising and falling vertically as calibrated by the accelerator pedal cable, while the fuel, which entered in a smaller amount through the lower part of the component, had to be sucked by a conical needle each time the intake runner valve was lifted, at the same time that the suction stopped when it was closed. The third was a constant depression carburettor, which maintained the air and fuel at low pressure. Rather unusual and only marketed by the English manufacturer S. U. at the time, it had an internal structure very similar to that of the variable air passage carburettor, although it worked in reverse: the accelerator pedal cable was not connected to the main jet opening and closing to regulate the entry of air and fuel, but moved a butterfly located at the end of the carburettor right before the engine. This created a backward depression —a vacuum effect— that opened the main jet and sucked the desired mixture towards the engine, without the need to exert the pressure necessary in the other two types of carburettors.[38]

A few months later, as Mañas continued exploring carburation, he came up with the concept of inertia as a key variable for those who studied carburettors for basically preventative reasons: whereas engines with a single carburettor supplying more than one cylinder did not waste fuel because it was mixed with an equal amount of air, when better engine performance was desired and a carburettor was mounted to supply each cylinder, the air-to-fuel ratio was three quarters of fuel for every quarter of air. This meant that the air was consumed faster than the fuel. As a result, when the main jet of the carburettor was closed, this produced an inertial effect on the excess fuel that caused its rejection towards the outside. Mañas proposed recovering this wasted fuel by designing a container attached to the carburettor that would collect all the fuel to be supplied from the start and repeatedly send it into the carburation cycle in proper amounts to mix with the doses of air.[39]

Examining innovations in combustion chambers in 1956, aeronautical engineers Segismundo Sanz Aranguez, head of the CETA laboratory department linked to

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[38] Mañas, J. (1954). Carburación. *Revista de la STA*, VI (21), 44–57 [in Spanish].

[39] Mañas, J. (1954). Diferencias características entre los carburadores según se destinen a la alimentación de un solo cilindro o de varios. *Revista de la STA*, VI (22), 35–41 [in Spanish].

ENASA, and Gregorio Millán, head of the aerodynamic studies division of the *Instituto Nacional de Técnica Aeroespacial* (INTA), led the publication of some essays that were not aimed at modifying the structure of combustion chambers as had been done in the early 1950s, but rather at adjusting minor activity involved in the ignition process. They started with the spraying action, when injected fuel became atomised into droplets: both engineers argued that the size of these droplets had to be as regular as possible to mix properly with air, which is more uniform and complete. The evaporation of these droplets would follow. Once mixed with doses of air, these droplets would then be subjected to powerful heat that Sanz and Millán recommended to be around 3,000º K by means of the compression ratio between the piston and cavities in the combustion chamber housed by the cylinder, fundamentally considering it the ideal temperature for ignition. However, if the laminar flame coming out of the spark plugs by default was insufficient, a turbulent flame could be produced that would significantly speed up its propagation through the air-fuel mixture.[40] This approach was clearly inspired by the study of air current turbulence originally reported by Jaime Miralles de Imperial.

In 1957, the editorial team of *Revista de la STA* drew up a state of the question on a very recent technological advancement that was still in the practical testing phase, despite the years of research behind it, and prompted Spanish engineers to look in the mirror, even though it had not even been implemented in Spain. This was Electronic Fuel Injection (EFI). Presented as an alternative to the carburettor fitted to petrol engines —and which would replace the diesel engine's pre-chamber injector at the end of the 20th century—,[41] it was detailed a long list of advantages such as more power at high revs, more low-end torque, more efficient fuel consumption and lower amounts of polluting gases emitted, alongside disadvantages like very high production costs, noisy operations, burdensome installation and fears that mechanical automobile repair workshops lacked the experience to introduce electronic fuel injection into serial production. There was a certain number of EFI devices made by some multinational specialised firms: American Bosch Arma Corporation, Robert Bosch, Joseph Lucas, Ramjet by Chevrolet, Bendix Electrojector, Fullcharger Corporation and Simmonds Aeroccessories.[42], but all were involved in a technology to which autarkic Spain did not have access; still, Spanish automotive technicians wanted to get to understand EFI, as it was a potential alternative for the carburettors with which they were widely familiar.

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[40] Sanz Aranguez, S., & Millán, G. (1956). La combustión de combustibles líquidos. *Revista de la STA*, VIII (28), 37–48 [in Spanish].
[41] EFI is connected to multiple sensors and to the Engine Control Unit (ECU), which intelligently determines the most efficient doses of air and fuel to be sent to the combustion chambers and can adapt to every circumstance of the engine's operations and avoid wasting resources as a result (Parissien, 2014, pp. 205–208, & 326).
[42] STA Editorial Team (1957). La inyección de gasolina en los motores de automóvil. *Revista de la STA*, IX (35), 29–39 [in Spanish].

After seventeen years with no new contributions to the study of combustion in internal combustion engines, in 1974 industrial engineer Domingo Cabarrocas Pruneda released a study aimed at identifying the substances inherent in fuel that wore out the pre-chamber injectors that supplied diesel engines. Discussing the important role played by impregnated paper filters for injector equipment, it was detected that the oil left both inorganic and organic elements on its surface, the latter more dangerous than the former. He therefore recommended frequently replacing such filtering components to prevent the combustion chambers from receiving fuel at an insufficient flow rate and pressure for supply due to the eventual obstruction of the injectors caused by waxes and asphaltenes.[43]

4. Discovering the best lubrication for diesel and petrol engines.

Whether an internal combustion engine is run on diesel or petrol, its mostly metallic components can only function properly with oils intended for lubrication, responsible for ensuring gentle contact between them and eliminating the damaging possibility of wear and tear.

In early 1951, an industrial engineer and laboratory chemical specialist named Emilio Lluch provided an overview of the precariousness of raw materials in autarkic Spain, when as historians say, it was established a system of ration cards for all goods available in low quantities: food limitations are widely known, but the automotive sector also suffered from industrial restrictions of steel, metallurgical materials, rubber, fuels, etc. (Preston, 2019, p. 366; Maluquer de Motes, 2014, p. 213). This is how we can understand Lluch's testimony deploring the alleged lack of supply of lubricants for the various automobiles: he wrote that in Spain, with an "insufficiently stocked market, the types and brands recommended are not found and the user's choice of the oil to use presents serious problems".[44]

It seems that the shortcomings he outlined were offset in the worst cases by the use of any lubricants that did not conform to the characteristics reported by the respective car manufacturers. However, even if no damage to the engines was clear in the short term, from his scientific experience he knew that it would appear in the medium and long term, entailing more frequent visits to the mechanic's workshop, a greater consumption of oil and fuel, difficulty starting in cold temperatures, damage to the spark plugs and so on. While lubricant suppliers performed a juggling act in the best of cases, trying to get oils to meet the requirements of each car as much as possible, Lluch actually advised both users and suppliers to focus on the required viscosity of the oily liquid and its degree of unctuousness, also discussing the possibility of adding additives to lubricants available in Spain to achieve the properties of others that were

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[43] Cabarrocas Pruneda, D. (1974). El circuito de combustible y su influencia en el desgaste del equipo de inyección. *Revista de la STA*, XXVI (97), 49–56 [in Spanish].

[44] Lluch, E. (1951). Características y especificaciones de lubricantes para motores. La lubricación bajo el punto de vista del cliente. *Revista de la STA*, III (9), 85–90 [in Spanish].

not available. Whatever the case may be, he impetuously recommended as suitable those lubricants whose viscosity varied slightly before changes in temperature and could constantly maintain the metals' protective molecular films.[45]

Two years later, in 1953 Manuel Serdá Torelló, the head of experiments and chief mechanical engineer at CETA, linked to ENASA, produced an extensive dissertation on lubricants that not only kept each and every mechanical engine component lubricated, but also had to prove unalterable when exposed to harsh working conditions inside the combustion chamber, such as high temperatures or the constant expulsion of gases.[46] Such effects were even more pronounced in diesel than in petrol systems where the oil blackened much more rapidly, becoming a soiled gummy or muddy substance —responsible of fatally seized engines— due to carbon particles in suspension coming both from the road and from successive combustions that not even the impregnated paper filters through which the fuel and oil passed were able to retain, as would be carefully studied twenty-one years later by Domingo Cabarrocas Pruneda.[47]

Based on the degree of unctuousness that Emilio Lluch had described as essential to guarantee the existence of a lubricant-based protective molecular film, which had to protect the contact between metal parts during mutual friction, Manuel Serdá Torelló went further and divided it into two subtypes: the degree of unctuousness of an oil that allowed fluid lubrication, in the sense that two or more components rubbed against each other but never quite touched thanks to the slippery liquid that lubricated them as planned, and the degree of unctuousness of an oil that worked with boundary lubrication, when the conditions in which it operated (temperature, pollution, etc.) refined the protective layer between the components to the maximum and intermittently suffered from dry friction, a risk scenario that could destroy the machinery if aggravated. With a critical tone levelled at the scarcity of resources in autarkic Spain, Serdá Torelló rised in a kind of representative collective voice attributed to the Spanish automotive engineers and concluded that the sad reality was that there were many lubricants in the market but few of guaranteed quality, and regular supply of the latter —essential for the national economy— was no longer reliable. For petrol engines, the problem of oil supply was generally not serious, but he said that the overall quality required by diesel engines caused several problems for users of good will who wanted to use the required oil so the engine of their truck did not have to be reviewed prematurely.[48]

In 1966, three petroleum chemical engineers, Francisco López de Miguel, of *Refinería de Petróleo de Escombreras, S. A.*; José Luis Martínez Cordón, of *Empresa Nacional Calvo Sotelo, S. A.*; and Aurelio Mompeán, of *Compañía Española de Petróleos, S. A.*, analysed different types of lubricants, quantitatively and qualitatively

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[45] Ibid., 85-90.

[46] Serdá Torelló, M. (1953). Engrase y lubricantes. *Revista de la STA*, V (16), 66–76 [in Spanish].

[47] Cabarrocas Pruneda, D. (1974). El circuito de combustible y su influencia en el desgaste del equipo de inyección. *Revista de la STA*, XXVI (97), 49–56 [in Spanish].

[48] Serdá Torelló, M. (1953). Engrase y lubricantes. *Revista de la STA*, V (16), 71–72 & 76 [in Spanish].

comparing and evaluating characteristics such as viscosity, viscosity index, freezing point, inflammation, foaminess, colour, density, carbon residue, sulphate residue ash and acidity index. These efforts prompted them to make a series of conclusions to recommend the best oils for specific engine work situations to automotive professionals on all levels and to automobile users in general.[49]

They made three distinctions for petrol engines. If subjected to mild conditions, a Regular-type, minerally pure and well refined oil without the need for additives was perfectly valid. For moderate demands that caused heating of the crankcase, making the oil so hot that it oxidised metal components, a Premium-type oil composed of corrosion-inhibiting particles and detergent substances had to be used. Finally, if the work required by the engine was severe, whether due to wear and tear from compulsively stopping and starting it (the case for transporters, taxi drivers, etc.), or due to overheating, they did agree that an oil with corrosion and wear inhibitors, as well as detergents and dispersants to avoid the concentration of harmful agents, was the most beneficial option.[50]

The same distinctions were made for diesel engines, following the load index they had to bear as a guideline. If it was low, there was no oxidation of heavy component wear, so normal Heavy-Duty oil could be used. If it was moderate, the same diesel fuel, with high sulphur content, could cause operational problems through deposits of gummy or muddy particles in such a way that the lubricant should reverse it, making the Heavy Duty oil Series 2 or Supplement the solution. Finally, if it was high, the accumulation of unwanted gum and sludge could obviously reach worrying rates that could only possibly be eradicated with Long Life oils with high detergency and could even allow travel for many kilometres without having to be changed.[51] These three engineers' final observations on diesel engine lubricant demonstrate a greater and better supply of quality oils for this kind of machinery in 1966, a scenario completely different from the lubricant supply shortage that Manuel Serdá Torelló had complained about in 1953.

The last innovation in automotive lubricants made during the Francoist Spain is highly specific: multigrade oils. Even though the team of petroleum chemical engineers made up of López de Miguel, Martínez Cordón and Mompeán had mentioned their recent emergence in 1966's research, it was not until well into the 1970s that their use spread as a sure thing. Given these circumstances, in 1974, one of the members of the aforementioned group, López de Miguel, argued that multigrade oils had nothing to do with the conventional oils known until the 1960s thanks to containing dispersants, detergents, oxidation inhibitors, anti-rust agents, anti-wear additives, viscosity index enhancers, freezing point depressants and antifoaming agents that made them the safest

[49] López de Miguel, F., Martínez Cordón, J. L., & Mompeán, A. (1966). Características de los lubricantes y tipos de servicios en automoción. *Revista de la STA*, XVIII (72), 54–66 [in Spanish].
[50] Ibid., 56–57 & 61.
[51] Ibid., 58–61.

option for all types of engines prone to problems, although such a wide composition increased both production costs and sales price. Yet their main feature, in accordance with their name, was the resilience to the work required in all kinds of situations without suffering much effect or variations in temperature, making them an attractive alternative for users who needed an engine that performed to the maximum in suboptimal working conditions, such as adverse weather, high transport load, unrefined fuel, successive stops and starts and so on. After conducting different chemical studies, López de Miguel concluded that this innovative lubricant product conferred the following advantages: first, it started up cold engines more easily, which avoided a high penalty for starting the engine and saved fuel; second, its constant fluidity greased the ducts and components immediately in all kinds of temperatures as soon as the engine was started; third, its optimal and continuous lubricating conditions prevented premature wear of the mechanics, so the engine remained cleaner and emitted less polluting gases while extending its useful life; and fourth, its virtually unalterable viscosity in any adverse scenario was the great secret to protect all engine parts and give automobile users peace of mind.[52]

Discussion.

This exhaustive analysis of the 32 selected articles on innovations in automobile engines published by the *Revista de la STA* between 1949 and 1974 documents automotive engineers' collective imagination during technological change in Francoist Spain and has uncovered satisfactory discoveries, problems, ill-fated attempts and concerns of all kinds that turned out to be the only way to make technological progress, based on the experimental method of trial and error. It reveals an impressive amount of inventions along with the processes carried out to achieve them, but a separate issue that deserves special assessment, given that the engineers almost never mentioned it explicitly, is the hardship imposed by the historical, political, social and economic contexts that professionals working in the automobile industry, and in any other field of technology, had to overcome to achieve their goals.

Indeed, the period studied between 1949 and 1974 coincides with the Francoist dictatorship, which never managed to make Spain one of the main world economies, and was not well-regarded by most neighbouring powers for its anti-democratic outlook, whether in its autarkic or developmentalist stage. Thus, and compared to most of the Western world, Spain suffered a delay in achieving real technological modernisation until developmentalism took hold in the 1960s. Franco's regime never was against innovation, but it had ushered in the previous autarky in 1939 as part of its politico-economic approach. Responsible for the harsh scarcity of primary resources available, the autarky stood in stark contrast to technical development in the country and even made it harder.

[52] López de Miguel, F. (1974). Los aceites multigrados y su utilización. *Revista de la STA*, XXVI (98), 30–56 [in Spanish].

It must be taken into account that the Francoist dictatorship chose and committed to a strategy of autarky between 1939 and 1959 both to: 1) isolate authoritarian Spain from democratic countries all around, except for export business with other European countries, some unavoidable imports and rapprochement with the United States in the 1950s due to Cold War geostrategic interests; and 2) as a repressive technique especially aimed at harming all non-fascist dissidents that had sided with the republicans during the Spanish Civil War (1936–1939), though in practice, fatal autarkic consequences were suffered by everybody, supporters and non-supporters (Richards, 1999, pp. 22–23; Del Arco Blanco, 2006, pp. 241–243). As such, the Spanish government's authoritarian nature was not ideal for encouraging steady technological development. In practice, however, the engineers' constant tenacity in creating innovations prevailed, and only this perseverance, verified by the evidence provided in this article, made it possible to meet Francoist Spain's automotive needs from autarky to developmentalism.

As widely demonstrated, the Francoist dictatorship depended on the innovations of so many Spanish engineers to put Spain on the path of modernisation, where it trailed the rest of the Western world, which had got a head start after the end of World War II. Spain was running behind schedule, because despite the impetus for research since 1949, documented by the *Revista de la STA*, its structural conditions would not improve until economic liberalisation after 1959. In any case, it is indisputable that automotive professionals gathered under bodies like the STA played a crucial role by doing everything they could get their hands on in good times and bad, seeking technological survival during the depths of autarky and subsequently rolling out new inventions and improving them to fill the roads with ever-more sophisticated automobiles within the range of industrial possibility, thereby promoting the developmentalism trumpeted by the dictatorship's propaganda and discourse in their own way and making it abundantly clear that the Francoist regime's technocratic shift starting in 1957 would not have been of much use without well-prepared automotive professionals fully able to transform Spanish society through the vehicles they created and manufactured.

These technical professionals repeatedly had to overcome scarcities of resources and technological shortcomings, more pronounced during the period of autarky than during that of developmentalism, and it was even possible to grasp their efforts in search of alternatives that could ingeniously solve the problems by themselves. With the passage of time and benefitting from a gradually improving socio-economic context, to which they had directly contributed with inventions that developed the technological modernisation of Spain, these people would acquire even more professional expertise and continue to make fresh progress for automotive companies, with access to more and better-quality raw materials and industrial machinery.

All in all, it has been realised that the great bulk of the innovations collected in *Revista de la STA* for the period between 1949 and 1974 came from a state-owned company such as ENASA, the manufacturer of Pegaso vehicles, and its experimental laboratory, CETA. There are two possible reasons for this. First, these companies were funded by the Francoist government through the INI, giving them an advantage in disseminating their innovations compared to private companies. Second, Wifredo P. Ricart, a founder and president of the STA, was also a respected director of ENASA and CETA at the same time, so he naturally gave high visibility to his talented discoveries and those of the rest of his team members first and foremost. What is odd, however, is that the engines of private companies without links to the government did not receive any kind of exposure in *Revista de la STA* and their important technological contributions were deliberately not covered, such as —among many others— Eduardo Barreiros' pioneering transformations from petrol engines to diesel engines since the early 1950s and his subsequent serial productions as part of his company *Barreiros Diésel, S. A.* (Thomas, 2007, pp. 169, 344 & 366; García Ruiz & Santos Redondo, 2003, pp. 73, 75, 78, & 83). In all probability, exponents like this were silenced because of the competition they posed towards the state-owned companies ENASA and CETA, as we must never forget that they both, as well as the INI and Franco's Ministry of Industry, tried to hinder the development of private initiative led by Eduardo Barreiros (see Figure 6) and *Barreiros Diésel, S. A.* as much as possible.

Figure 6. Eduardo Barreiros at his office (FEB, wo/d).

Conclusions.

This careful study of the scientific projects initiated and explained by automotive engineers in their own words aims to address the gap in our knowledge revealed by Darina Martykánová (2021, p. 310), namely the lack of historical-sociological approaches to the professional association of engineers, due to the absence of any academic trend or school interested in studying the professions in Spain. This effort has identified numerous technological steps forward in the design, construction and improvement of all types of engines, while tracing the technological development of Spanish automobiles over the timeframe of the study (1949–1974), thanks to its long-term perspective and broad scope.

Thus, after briefly considering the importance and contributions of the STA to Spanish automotive engineering, the research first explores work on diesel engines and the establishment of a diesel culture, driven by the significant fuel savings they offered for frequently used vehicles, particularly taxis, trucks and buses. It then examines improvements to all the mechanical components involved in the internal combustion process of diesel and petrol engines. Finally, it focuses on the lubrication of diesel and petrol engines, through various experiments aimed at achieving optimal performance.

In this way, the article's main objective —analysing the automobile's role in technological change during Francoist Spain— has been fulfilled by considering the collective imagination of professionals in the automotive industry. This mental framework, as stated throughout the research, did not remain static, but rather went through two distinct phases during the dictatorship.

On the one side, in the 1950s automotive engineers combined their efforts on innovations with a critical and occasionally dissenting stance against the rules of economic autarky. However, this bold commitment was limited —presumably due to the fear of expressing oneself freely under an authoritarian regime—, meaning that they continued to face challenges in accessing the necessary resources and technologies throughout the decade.

On the other side, the resilient minds of those automotive engineers shifted from resignation to optimism in the 1960s and 1970s, as they saw their ideas, capabilities, knowledge and expertise gain greater significance. It was largely due to improvements in primary means and industrial machinery driven by the new developmentalist economy, to which they had undoubtedly contributed through their unwavering dedication to their professional mission: to achieve the best possible technological progress for Spanish automobiles, regardless of economic conditions.

None of this would have been possible without the historical source *Revista de la STA*, the journal published by the *Sociedad de Técnicos de Automoción* (STA) in which automotive engineers used to disseminate their own technical research, representing the companies they worked for. Moreover, the article highlights that *Revista de la STA* had a clear preference for showcasing engineering advances made by state-owned companies —particularly those carried out under ENASA and CETA—, while leaving no space for engineers from private automotive firms.

Acronyms and Abbreviations.

ASTA: Archive of the Sociedad de Técnicos de Automoción.
BOE: *Boletín Oficial del Estado*.
No.: number.
Vol. / vols.: volume / volumes.

Wo/b: without box.
Wo/d: without date.

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Conflicts of interest.

The author declares no conflict of interest.

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Інновації автомобільних двигунів в Іспанії часів режиму Франко через *Sociedad de Técnicos de Automoción (STA)*, 1949–1974

Анотація. *В Іспанії спостерігається нестача історико-соціологічних підходів до аналізу професійних об'єднань інженерів загалом, а особливо автомобільних інженерів. Це пов'язано з відсутністю академічних шкіл або напрямів, зацікавлених у вивченні професій. Саме тому метою цієї статті є дослідження технологічних змін і розвитку автомобільних двигунів, що вироблялися в Іспанії за часів режиму Франко, на основі інновацій, створених фахівцями іспанської автомобільної промисловості, описаних ними самими. Наше дослідження спирається на теоретичну основу культурної історії та її підходів до колективної уяви, що розуміється як ментальна або свідома структура, яку можна досліджувати настільки, наскільки вона поділяється членами певної людської спільноти й стосується їхньої ідентичності – у нашому випадку, іспанських автомобільних інженерів. Обрана методологія полягає в аналізі історичної наукової преси: розгляд 32 статей, написаних інженерами для журналу Revista de la STA і опублікованих Sociedad de Técnicos de Automoción у 1949–1974 роках, дозволяє зазирнути у колективну уяву цих фахівців. У своїх публікаціях вони описують власні винаходи та процеси, що до них призвели, висвітлюючи як успішні відкриття, так і проблеми, невдалі спроби та різні занепокоєння. У роки франкістської автаркії автомобільні інженери стикалися з великими труднощами – фінансовими обмеженнями та браком ресурсів – у процесі реалізації своїх інновацій. Натомість у період розвитку, що настав після економічного стабілізаційного плану 1959 року та відзначався кращими соціально-економічними умовами, вони змогли перейти до експериментів з більш складними технологіями. У такий спосіб діяльність автомобільних інженерів зробила суттєвий внесок в економічне зростання Іспанії за часів Франко, допомагаючи подолати злидні 1940–1950-х років і забезпечити перехід до споживацького суспільства 1960–1970-х. Зрештою, стаття робить висновок, що журнал Revista de la STA, використаний у дослідженні як історичне джерело, демонструє явну прихильність до інновацій, створених інженерами, пов'язаними з державними автомобільними компаніями, нехтуючи при цьому розробками з приватного сектора.*

Ключові слова: *автомобіль; інженерія; технології; інновації; франкізм; іспанські інженери*

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History of electrification in Tashkent during 1914–1918 years

Abstract. *After the colonization of the Turkestan region by the Russian empires in the second half of the 19th century, the tsarist authorities chose the city of Tashkent as*

the political, administrative and military center of the entire region. This was primarily due to Tashkent's trade and economic superiority over other cities, and secondly, the city's location in the central part of the country and its strategic importance. Although the industrial sectors were poorly developed, work began on the construction of power plants to illuminate the city streets and operate small manufacturing enterprises. The main focus was on Russian and foreign capital, and the initial projects were not implemented due to the bureaucratic system. Although the number of power plants operating in Tashkent increased somewhat in 1914–1917, they were used only for lighting buildings and streets of social importance, not for industrial purposes. By 1914, the Russian Empire ranked 8th in the world in terms of electricity production, with 14 kWh of electricity per capita in the central parts of the empire, while in Tashkent this figure was only 1 kWh per capita, indicating that the metropolis's attention and fundamental interests were directed to other things, rather than the development of the city's socio-economic sectors. Although the participation of the Russian Empire in the First World War gave impetus to the increase in production in the food, textile, and military industries, there were no noticeable changes in the energy sector. In particular, although attention was somewhat increased in Tashkent in 1914–1918 to the construction of power plants, financial difficulties for investors and the complex political changes of the time negatively affected the number of people at the helm of this work, which led to the postponement of planned work. Economically, Tashkent and its surroundings, as an industrial-agrarian region, have the potential to introduce various infrastructure systems, have vast natural raw material reserves, and have all the conditions for the construction of hydroelectric power stations, but these natural opportunities have not been fully utilized.
Keywords: *Tashkent; electrification; electrical power station; contract; lamp; tram*

Introduction.

In the 21st century, the constant increase in demand for mineral resources for the purpose of energy production is the reason for the strengthening of geopolitical rivalries. It is explained by the study of the slowness of electricity production in industry and other sectors in the end of the XIX century – the first quarter of the XX century and its negative impact on the development of the socio-economic and cultural life of the people of the country. At a time when world economic relations chose new directions of development and began fundamental changes on this basis, the conflict situation in colonial Turkestan did not allow for timely assimilation of technical innovations and implementation of large-scale measures of their introduction into industry. This can be observed in the colonial administration’s old-fashioned way of turning the country into its own raw material reserves, with a primary focus on the agrarian issue and neglecting the development of industrial sectors. The process of electrification of the Turkestan region also experienced the same complex historical reality, and as a remote country, initially during the colonial period, and later under the

Soviet rule, it lagged far behind the indicators of electricity consumption in the central regions. Such disparity and other important issues of the field require a new approach to the problem, understanding of their roots and historical scientific evaluation.

In a number of works that examined the issue of electrification in the regions and large cities of the Russian Empire, it was noted that the electrification of Tashkent at that time was at a low level than other parts of the empire (Simonov, 2016; Simonov, 2017). In works devoted to the history of the region and its industry during the colonial period, it is noted that the electrification of Tashkent, which was the political and administrative center of the Turkestan Governorate, was carried out last of all other cities in the empire (Musaev, 2008; Abdullayev, Rakhimov, & Rajabov, 2019). A number of other scientific studies devoted to the socio-economic history of Turkestan in the late 19th and first quarter of the 20th centuries have analyzed in detail the low level of the Tashkent city's industry and technical condition, and the main attention of the colonial administration was paid to raw materials from agriculture (Shadmanova, 2011). Some researches revealed that the number and technical equipment of industrial enterprises in the Russian Empire lagged behind European countries and the USA, which also had the bad an impact on the economic situation of Tashkent that period (Khaydarov, 2018; Makhmudova, 2018).

Colonial nature of the economic policy of the Russian Empire in Turkestan's cities during the First World War, noting that the colonial administration, by placing various artificial obstacles to the development of manufacturing industry in Tashkent, tried with all its might to develop cotton growing in the country (Tukhtabekov, 2015).

It was only during the implementation of the GOELRO plan that the electrification process in the socio-economic and cultural life of Tashkent accelerated, and the Turkestan Commission created for this purpose had a separate financial fund (Timurov, 2015; Yeryasheva, 2018). Some works considered the establishment of the first higher educational institution in Tashkent –Turkestan People's University and its Technical faculty and the training of technical personnel there, as well as the sending of local youth to study abroad and improve their skills there (Kholboev, 2003; Turdiev, 2006; Irzaev, 2018).

On the eve of the World War I, the Dumas of the cities located in the Russian Empire were unable to function as a democratic organization representing the interests of the people (Soloviova, Hurinchuk, Berdnychenko, & Strelko, 2020). This situation is also characteristic of the Tashkent city Duma, the Duma members, whose management system consists of tsarist officials, retired generals and officers, worked for their own interests and did not think about the affairs of the city. Even "Izvestia", the printed edition by the Duma, reproached the persons sitting in the Duma apparatus, saying that "they often did not work with zeal, but served" (Izvestiya Tashkentskoy gorodskoy Dumi, 1916, p. 476). Such persons without initiative and responsibility in the Duma sat for the specified term of office, signed the included papers, received the visitors, and after leaving the power, they forgot about the concerns of the city.

At the moment, revitalization of beautification works in the city, development of lighting systems was an urgent issue. Due to this, in April 1914, projects of a hydroelectric power station and a water pipeline were considered under the Tashkent city administration. At the meeting, professors A. I. Astrov and V. D. Sokolov (Technical college), V. V. Dmitriev (Petersburg Electrotechnical Institute), A. K. Yensh (Riga Polytechnic Institute), technical managers of the Moscow water supply organization and local engineers and doctors from Tashkent participated. It was unanimously decided that Bozsuv canal of Salor brook was chosen for the construction of the hydroelectric station and water supply facilities (Turkestanskiy kuryer, 1914).

The planned power plant should to be used mainly by lighting and water supply consumers, and the "Belgian society" did not envisage electricity supply for trams. This would not ensure the full use of the hydro-station, and since the owners of Salor canal's arable land have priced the land at a high price, their purchase would have automatically increased the cost of the hydro-station and the water pipeline.

All these combined forced the city administration to temporarily stop the implementation of this project before the beginning of the World War I. But the activities of the Belgian "Tashkent tram" company in providing electricity to the whole city were so huge that the only way for the city administration to fight against it was to build its own power station, only in this way it could have a monopoly on the city's electric lighting.

If Pavlov's station was purchased by the Belgian company "Tashkent Tram" by the city administration, it would expand in the future and complicate the implementation of the project of construction of the power station intended by the city. Therefore, the head of the city N. G. Mallitsky while in Petersburg in March 1914, persuaded the Russian Minister of Defense not to allow the "Tashkent tram" society to start electric lighting works. Although this will cause great damage to the city, the community has won this right (Turkestanskiye vedomosti, 1917). However, in the "law" announced on April 22, 1914 with the signature of the Minister of Trade and Industry, amendments were made to the charter of the Belgian "Tashkent Tram" company, and it was allowed to start electric lighting works. As a result, the city authorities of Tashkent lost the right to own the city enterprises with the "Tashkent tram" company.

Speaking at the City Duma on October 19, 1917, N. G. Mallitsky stated the following: "In Russia, a number of Belgian joint-stock companies with millions of capital are operating in the field of starting electric (tram, electric lighting) enterprises. They are using Belgian diplomatic representatives to protect their interests. Also, special representatives are kept in St. Petersburg to carry out their projects from the central offices. ...Foreign companies prefer to complete their work through central agencies, denying Russian society the rights of self-governing agencies" (Turkestanskiye vedomosti, 1917).

Research methodology.

In the process of studying this problem, special attention was paid to the comparative historical method, which allows identifying and comparing the levels in the development of the process being studied, the changes that have occurred, and determining development trends. With the help of the comparative historical method, which identifies the general and the specific in historical phenomena by comparison, knowledge of the various historical stages of development of the same phenomenon or two different coexisting phenomena is achieved.

And also used the statistical method, which allowed tracing the quantitative parameters of the historical process of researching of that period.

Results and Discussion.

It should be noted that before and during the World War I and even after, the majority of the local population mainly lit their homes with candles, and there were shops selling candles in the bazaars. In below by Figure 1 we can see such little local shop in Tashkent, which were distributed in many small towns and large cities of all Turkestan (NACFPh Uz (National Archive of Cinema, Foto-phono of Uzbekistan. No. 0-93844).

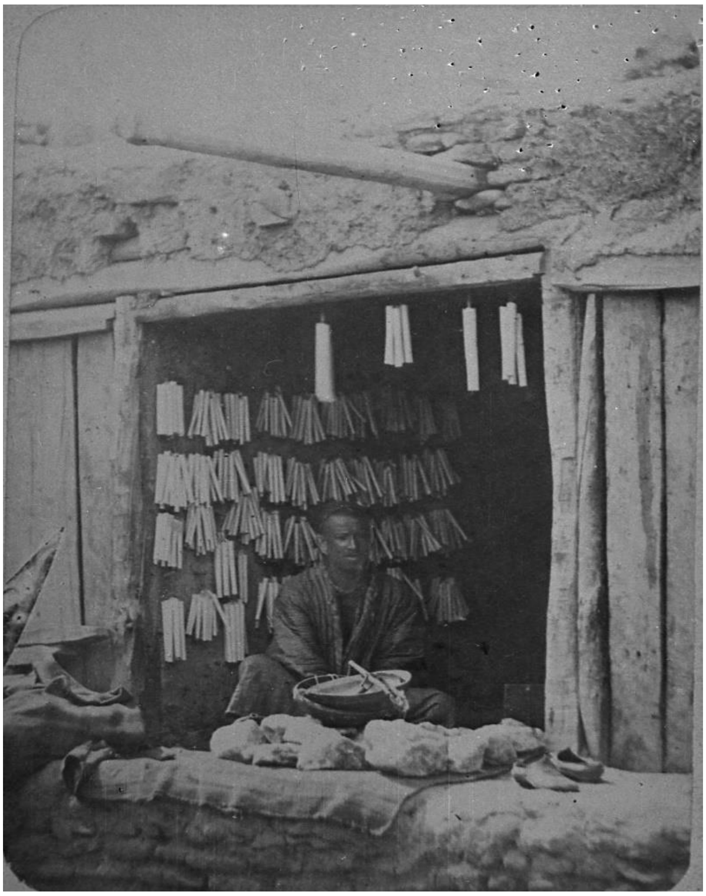

Figure 1. Candles shop in Tashkent local bazaar (NACFPh Uz (National Archive of Cinema, Foto-phono of Uzbekistan. No. 0-93844).

From June 1914, preparations for the construction of the thermal power station were started in central city of Turkestan – in Tashkent. It was intended as a backup for the future hydroelectric station. On July 20, 1914, two 350 horsepower (hp) diesels were ordered for the Kolomensk plant, for which a deposit of 10,000 rubles was transferred (Turkestanskiye vedomosti, 1914).

Ilinsk Square (around Oloy Bazar) was chosen for the thermal power plant. The beginning of World War I, financial difficulties slowed down the pace of construction of the temporary station.

The official request of the city administration to the Minister of Finance Uvarov to open an account with a pledge of 1,650,000 rubles in the state bank was not satisfied. The Russian Imperial Ministry of Finance considers it "not very necessary" to build a power plant in the city (NAUz (National Archive of Uzbekistan). F. I-1. D. 1. C. 1890. S. 13).

In this way, the city's attempts to build a temporary power station, then a hydroelectric power station, and finally a thermal power station, deprived it of the capital provided by the imperial treasury. Later, the head of the city said that after 5 years, the hydroelectric power station can be built and put into operation, and until then, the temporary power station will bring a profit of 22,000 rubles (NAUz (National Archive of Uzbekistan). F. I-1. D. 3. C. 1670. S. 19).

Due to the need for electricity, the city administration was forced to negotiate with the community to strengthen the former station of Pavlov. On December 18, 1914, an additional agreement was signed between the city and the society, according to which the society was allowed to transfer excess electricity to Pavlov's station under the following conditions:

1. The city grants the society the right to transfer the necessary amount of electricity to Pavlov's station according to the specified plan to drive the 60 hp electric motor dynamo machines at the central tram station.

2. The society undertakes to pay the city 3 kopecks for each kWh of energy transmitted to the city for the right to use the electric energy transmitted from the tram station, as well as the city streets, narrow streets and squares based on this contract (NAUz (National Archive of Uzbekistan). F. I-44. D. 1. S. 283).

The newspaper "Turkestanskie vedomosti" dated December 19, 1914 published the news that the city administration had signed an additional contract with the "Tashkent Tram" company, and informed that the needs of all consumers who have not yet been supplied with electricity will be met in the near future3.

In the fall of 1915, the number of electricity consumers increased dramatically, and the work of V. P. Pavlov's station exceeded the established norm. The city administration received dozens of applications from state organizations and individuals asking for permission to supply electricity.

According to the situation, City Duma (between the city) with V. P. Pavlov to amend the charter concluded in 1911 and decided to provide the right to strengthen V. P. Pavlov's former station with one more motor with a capacity of 150 hp. Until the installation of this engine, the society temporarily received electricity from the central tram station to V. P. Pavlov's station received a sufficient amount of transmission with the help of a 75 hp (NAUz (National Archive of Uzbekistan). F. I-44. D. 1. C. 122. S. 1).

After install of the motor-generator in V. P. Pavlov's power plant, the 140 hp engine broke down soon and could not be repaired due to lack of spare parts. In this way, many consumers were left without lamps, The society was allowed to add one unit to the tram station to run the lighting system of the V. P. Pavlov power station (NAUz (National Archive of Uzbekistan). F. I-44. D. 1. C. 251. S. 71). Despite the fact that there was a clear direction to build a diesel power station with a hydroelectric power station, this project was also not implemented.

The Belgians gradually began to acquire new projects for the electrification of the city in return for various promises. During this period, the city's plan to build its own hydroelectric power station faced a number of insurmountable obstacles. The design power of the hydroelectric station was designed for 3,000 hp. Thus, the technical side of the problem was quickly solved. But it was somewhat difficult to solve organizational issues from the point of view of the current legislation. Because water had to be used primarily for agricultural purposes, then for shipbuilding, and thirdly for the purposes of "water movement" (Saidboboeva, 2021, p. 88).

In addition, the problems of cotton ginning factories, which worked only four months in the winter season at that time, as energy consumers, were also added. This did not take into account the usual consumers (hydraulic mills, mills, rice mills, etc.), whose devices and equipment were simple and simple, and it was difficult to predict that they would switch to electric motors.

During this period, electricity was mainly used for lighting purposes, and its role in the use of power tools was very small. For example, in 1914, the share of electricity in breweries with a total capacity of 214 hp was 80 hp or 38%, and cotton gins only 16%.

Despite the weak industrial development, there were 50 different industries in the region. The most important of them is the processing of agricultural products, the total volume of industrial production was 13,388,6778 rubles (1913), the number of workers employed in it was 20,925, the total number of enterprises was 702, and the number of engines in it was 507 (Aleksandrova-Zaorskaya, 1964, p. 210).

In 1914, while there were 223 cotton ginning factories in Turkestan, the number of power stations was only 36. Correspondingly, 96,177,163 rubles of cotton ginning factories, and only 242,435 rubles of power stations, in terms of production in the country's industries.

The technical backwardness of the country has led to the low level of electrification. Only in 1914, the total capacity of all power stations in Tashkent was 3,000 kW, producing 3.5 million kWh of electricity per year. In the years 1910–1917, several central power stations in the country operated only in the city of Tashkent.

Their total power was 5 thousand hp or 3.7 thousand kW, which was only 1.85% of the total power in Petrograd.

Tashkent's 1916 electricity performance can be seen in below (Table 1; Table 2) comparing it with the capital of the empire – Petrograd (Kaminsky, 1931, p. 56):

Table 1. Electrical power stations in Petrograd (1916).

Name of the electrical power stations	Power, (thousand kW)	Type of direct current (Voltage)	In volts
1886 year's society	40,2	3 phases	2000 and 6000
Gelios	12,8	1 phases	3000
"Belgian society"	12,1	1 phases	2000
Tram	No data	Direct current (DC)	600

In addition to the above stations in Petrograd, there were also many stations for general use, called block stations, which served individual consumers.

Table 2. Electrical power stations in Tashkent (1916).

Name of the electrical power stations	Power, (thousand kW)	Type of direct current (Voltage)	In volts
Pavlov	0,125	direct current (DC)	2×220
Davidov	0,231	direct current (DC)	2×220
Tram	1,450	direct current (DC)	600
Shamsutdinov	0,045	direct current (DC)	2×220

About 70 electricians, 55 shift diesel workers, and 94 black workers performing various jobs worked in Turkestan power stations. During this period, 168 of the 702 main enterprises were equipped with electric lighting using their own independent generators. Despite the insufficient production of electricity and such a low level of electrification, there have been significant changes in the country's industry.

The Russian Empire, which was mute to foreign capital, had to import electric lamps from foreign countries in addition to machinery and technical equipment.

The situation in the metal manufacturing industry was similar. For every 15 mechanical engines in the industry: 13 internal combustion engines with 170 hp, one locomotive with 24 hp and 1 water engine (water blade) with 12 hp. Only one of the metalworking enterprises had a 5 hp electric motor. During the colonial period, electricity was mainly used for lighting purposes, and only 15–20% of it was used as a driving force (Saidboboev, Musaev, & Saidboboeva, 2020, p. 453).

The state of electrification of communal economy was also very low. Even in big cities such as Tashkent, Samarqand, Kokand, Fergana, Andijan, only 2–3 streets are lit with electricity, the rest of the streets are partially lit with gas, and the rest are completely unlit. In three or four cities, the houses of some big officials were also lit by electricity. Although small power plants began to operate in the industrial enterprises of Turkestan at the end of the XIX century, by the first decades of the XX century, with the growth of the industry and the emergence of power plants for general use, energy was formed as an independent industry in the industry.

The number of workers working in the existing power plants in Turkestan was also not that large. According to the statistics published in 1915, a total of 151 workers were employed in the industry during this period. For comparison, if we take into account that 7626 workers worked in the country's cotton ginning industry in the same period the above figure seems to be quite low(NAUz (National Archive of Uzbekistan). F. I-1. D. 2. C. 432. S. 78).

The growth of the industrial and transportation sectors during World War I stimulated the increase in the number of workers in the country. In 1914, there were about 50,000 workers in the main industrial regions of the country, and during the war, the working class in Turkestan increased by 15-20,000 people and reached approximately 70,000 people (NAUz (National Archive of Uzbekistan). F. I-278. D. 2. C. 716. S. 35).

The increase in the number of workers initiated qualitative changes in the national economy of Turkestan, and created the basis for the emergence of new industrial sectors, including energy, along with the general growth of enterprises.

In 1916, the imperial authorities developed plans to exploit the water reserves for economic purposes, but despite the large hydropower wealth in Turkestan, most of the stations were oil-fired. Oil for these stations is mainly brought from Baku, which was expensive for the country. However, especially during this period, the Volga River was the main factor in the transport system and trade exchange, economically connecting the districts of the empire with its tributaries. It transported fish from the Caspian Sea, cotton from Turkestan and a large amount of factory products from other regions. Every year, 30 million tons of such cargoes are transported along the river and its tributaries (Simonov, 2016, p. 143).

The steady increase in demand for electricity in the country forced the administration to look for new sources of energy. According to the decision of the General Artillery Department of the Military Council on November 5, 1916, in the telegram sent to the military governor of Fergana region on November 10, it is said that Count de Monge and Davidov, an engineer-hydraulic engineer of the Department of Land Affairs and State Property of the Turkestan region, were assigned the task of studying the waterfall in Isfayramsoi in the Maidan and Uchkurgan districts of the Skobelev district of the region (NAUz (National Archive of Uzbekistan). F. I-276. D. 1. C. 936. S. 164).

In order to ensure the implementation of the decision, the local administration will provide the researchers with: 1) previous projects for the construction of a hydroelectric station in Isfayramsoy (1914) and all information about the river in general;

2) providing the necessary means of transportation from the city of Skobelev to Maidan at current prices; 3) assigned the task of providing all-round assistance for hiring and other needs of workers.

On the basis of the above letter, on November 21, 1916, the military governor of Fergana region sent an open order to the officials of the Russian and local administrations in the region to unconditionally fulfill these tasks (NAUz (National Archive of Uzbekistan). F. I-276. D. 1. C. 936. S. 165).

In 1917, one of the two city central power stations in Tashkent was the Shamsutdinov power station, and the other was N.K. Romanov's renovated power station (NAUz (National Archive of Uzbekistan). F. I-1. D. 1. C. 291. S. 1).

All the power plants in the country of Turkestan are mainly concentrated in industrial and cultural centers, 32 of them, i.e. about 16% of the country's power plants, were located in the city of Tashkent. They were considered the largest power plants of their time and distinguished by the large number of workers. Among the 22 power stations under the industrial enterprises of the city, Tram power station employs 18 people (NAUz (National Archive of Uzbekistan). F. I-44. D. 1. C. 237. S. 17) and 10 people work at the power stations under the Central Asian Railway Workshops.

There is no information about the workers at the Yusuf Davidov's electr station.

The remaining 19 small electrical devices were serviced by 1-2 people mainly for lighting purposes. Thus, 60-65 workers were employed at the power stations of the industrial enterprises. In terms of numbers, the second place was occupied by workers working at 10 power stations serving the city's communal economy. The biggest of them is V.P. Pavlov's power station is considered, and out of 9 people working in them, 5 were employees and 4 were workers working at the central station. Monthly wages for employees: 300 rubles for an engineer, 100 rubles for an accountant, 100 rubles for 2 office workers, 25 rubles for a document carrier; for workers: 120 rubles for a machinist, 100 rubles for a machinist's assistant, 35 rubles for an electrician, 45 rubles for a plumber (NAUz (National Archive of Uzbekistan). F. I-44. D. 1. C. 244. S. 11).

The same amount of salary is typical for small power stations, according to the reports of Max Visokinsky, who leased the Khiva cinema and the Knyaz Romanov power station, where 3 workers (electromechanic Ozolin with a monthly salary of 120 rubles, and two assistants with a salary of 40 rubles) (NAUz (National Archive of Uzbekistan). F. I-40. D. 1. C. 172. S. 20).

The average annual wages of power plant workers were 3,7 times that of cotton gin workers and 2 times that of machine shop workers in 1913, compared to the average annual wages of workers in other industries.

Due to the shortage of electricity, working conditions in the country's industrial enterprises were very difficult. The working day lasted 14 hours, and in most enterprises the workers worked 18 hours, and they were paid very little. In 1913–1914, the average annual salary of one worker was around 180 rubles (Ziyodullayev, 1964, p. 13).

Moreover, in 1917, the number of enterprises operating in Turkestan decreased by 75% compared to before the war. Industrial production was reduced by 80% Desyatchikov, 1949, p. 18). Although the workers of the power plants had better conditions in many respects (salary, working conditions) than the workers of other enterprises, they had a feeling of dissatisfaction with the government and politics.

In particular, the initiators of many strikes that took place in Turkestan at the end of 1916–February 1917 were Russian and local railway workers and workers at the Tashkent tram depot, among whom there were many women. The Turkestan district security department worriedly said, "The mood of the workers is not calm. Failure to meet the urgent needs of railway workshop workers may cause continuous strikes and may be a signal for strikes in other enterprises as well" (Kastelskaya, 1980, p. 94).

Later, in the armed uprising of workers and peasants on October 28, 1917, the workers of power stations also participated.

There are a small number of small manufacturing enterprises in the country, and they did not fully carry out their activities for several reasons, first of all, because the state did not support them, because Turkestan was considered as an additional raw material part of the empire. Also, if we take into account that the number and technical equipment of industrial enterprises in the Russian Empire lags behind European countries and the United States, this also did not affect the situation in its colony (Saidboboyev, 2015, p. 30).

Most of the equipment of industrial enterprises was old equipment imported from metropolitan enterprises.

Foreign economists saw industrialization not as a method of ending the inequality of nations, but as a method of strengthening their backwardness and weakness. They argue that this concept was preserved and even developed in Turkestan in the period before World War I, which was inherited from the colonial tsarist system. According to them, the industrialization policy strengthened Uzbekistan's status as a source of raw materials for Russian industry (Saidboboyev, 2010, p. 99).

The fact that the country's weak factory industry, including the industry that only pre-processes agricultural products, primarily cotton, does not contribute to the creation of the necessary conditions for the development of the electrification sector, and the administrative and management system of the region, which serves the interests of the metropolis, has not thought of ways out of this stagnation and did not develop quickly.

On the eve of the First War I, the "Belgian society" ordered 80 cars from the "Rateno" factory (Belgium) to start the electric tram line. Each carriage has 40 seats and 2 freight carriages are also included. The tram park is located on Mariinsky (now Nukus) street. Trams were supplied with electricity by a newly built diesel station.

The power plant was equipped with five 430-liter diesel engines, each with a permanent one-shaft electric generator, with a total power of 290 kW and a pressure of 600 volts. The total capacity of the power station was 1450 kW per day. Although the contract stated that the 600-volt power plant was not intended to supply electricity to the city, its switchgear circuit was designed so that it could operate at 220 volts under any circumstances and meet lighting needs.

Low production of electric energy has had a negative impact on the increase of tram routes, population transportation, and income generation. For example, at the eve of World War I, when the population of Tashkent was 250,000 people, the total length of the electric tramway was only 18,3 km. However, in many other cities of the empire with a small population (not including Petrograd, Moscow), the length of electric tram routes was several times longer than in Tashkent, as can be seen in the following Figure 2 (NAUz (National Archive of Uzbekistan). F. I-37. D. 1. C. 413. S. 45) and in below Table 3 which are based on the data of National Archive of Uzbekistan (NAUz (National Archive of Uzbekistan). F. I-37. D. 1. C. 476. S. 11):

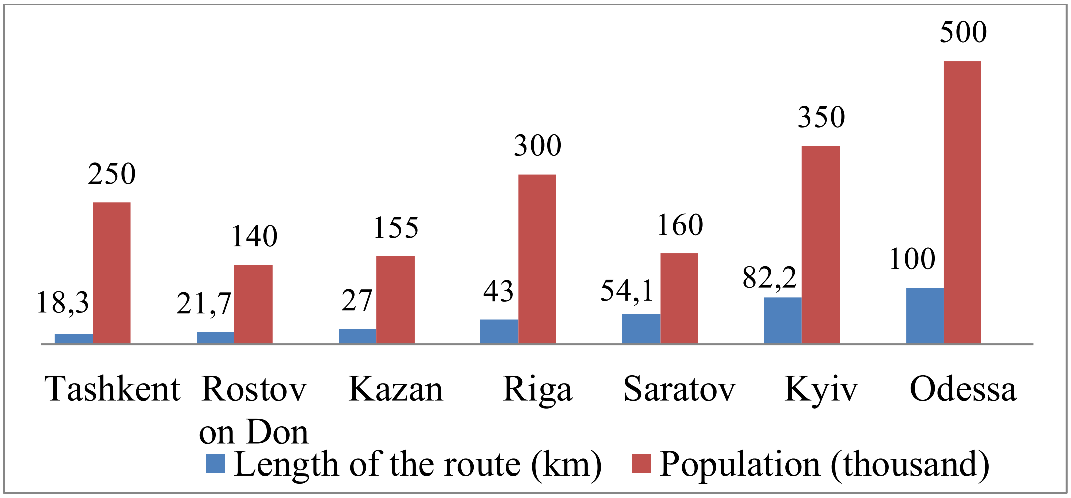

Figure 2. Length of tram routes and population in Tashkent and other cities of the Russian Empire (Eve of World War I) ((NAUz. F. I-37. D. 1. C. 413. S. 45).

Table 3. Electric tram revenue calculation in Tashkent and other cities.

City	Length (km)	Population (thousand)	Gross profit (thousand rubles)	Profit from 1 person	Transportation one person (in year)
Tashkent	18.3	250	550	2.2	44
Riga	43	300	1830	6.1	122
Kyiv	82.2	350	3330	9.5	190
Saratov	54.1	160	925	5.8	116
Odessa	100	500	2700	5.4	108
Kazan	27	155	556	3.6	72
Rostov on Don	21.7	140	1070	7.6	152

In the article published in the issue of "Turkistan viloyatining gazeti" on May 29, 1914, the advantage of the tram was mentioned, "13–14 years ago, if we wanted to go to the train station or the Sunday market, we would have to walk for two hours with our country's fast-moving cart, and our feet (feet) we were torn to pieces, our hearts were turned upside down, and our souls were coming to our throats. Praise be to you, we got rid of such consequences and began to enjoy the wonderful science of the 20th century". Author expressed satisfaction and at the same time, the article urges the residents to use the tram in an orderly manner: "... if you are blind with a blind eye, squint your eyes. This proverb was left over from earlier. When our neighbors told us to take a step to the right side, become righteous, and follow the path of education, we turned the letter upside down, we don''t know where our feet are, and we don't remember our past situation, we keep walking in the cave of ignorance, and all this is a loss to us. Because of our chaos, the government has appointed mirshab and guards to protect the city" (Mirmuhsin, 1914).

Another article talks about the success of electrical engineering, and there is great hope that the telegraph will become popular in European countries and enter Turkestan as well: "In Europe, science is progressing and developing day by day, and many crafts are emerging that are useful to various people. One of the inventions of European science and culture is the wireless telegraph. Although this day has just been released, these days mankind has developed and progressed to a surprising extent. On a new occasion, with this wireless telegraph, standing at two stations with a distance of 12,500 miles, two people talked that this distance, that is, the distance between the two stations, is one-third of the circumference of the earth" (Turkiston viloyatining gazeti, 1916).

In 1914, other tram routes were also electrified. In particular, the Pushkin route was opened from the Church of St. Sergius to the Salor bridge, the Moscow route was opened from the Knyazhesky fortress to the Beshyogoch gate, and at the beginning of 1915 to Chorsu, and on December 13, 1915, the fifth electrified tram route was opened from Kokaldosh to the Takhtapul gate through Eski Jova.

By 1916, the "Tashkent Tram" society, which saw the gratitude of the population, started using 50 motorized, 25 cargo and 2 service wagons in Tashkent. In the same year, the company took the leading place in the field in terms of the amount of energy supplied to consumers by power plants of Tashkent city (1450 thousand kW).

At the same time, it is worth noting that with the active participation of the public and city authorities, the Belgian "Tashkent Tram" company's desire to deprive the city of its ownership of the lighting systems caused a number of difficulties for the community. The society's efforts to provide direct current (DC) energy to the tram lines were condemned, and the city administration was on the verge of becoming a monopoly customer in this field.

From September 10, 1918, the tram service stopped due to the lack of fuel at the city diesel station and the failure of many cars. This was due to the change of the political situation in the country and the departure of experts from Belgium to their homeland as a result of the establishment of Soviet power. Soon after, on December 10, 1918, the "Tashkent Tram" was nationalized by the Central Executive Committee of Turkestan, and only by 1920, irregular tram traffic was restored in the city.

Figure 3. Workers of Tashkent nationalization tram (NACFPh Uz (National Archive of Cinema, Foto-phono of Uzbekistan. No. 0-93973).

In this way, although the process of electrification of the transport system in the country has been opened, the lack of a clear plan and measures for its rapid development, financial difficulties and laxity in the issue of personnel shortage have hindered the slowdown of work in the field and its competitiveness.

However the coming of the electric power industry in Turkestan required the training of highly qualified electrical engineers, electrical fitters and management personnel for the system. The geographical location of the region far from the central parts of the country, the fact that the Soviet regime did not yet have strong governing bodies in the country, the civil war, and economic difficulties all delayed the most necessary work in this direction.

In 1918, the work of establishing a leading educational institution for the training of highly educated personnel in engineering and technical specialty was started in Turkestan. For example, on March 16, 1918, the Council of People's Commissars adopted a decision to open a People's University in Turkestan, which stipulated that all expenses for the establishment of the People's University will be made at the expense of the trade turnover of nationalized cotton, oil and coal.

On April 11, 1918, the first meeting of the technical faculty of the Turkestan People's University was held, and "in this way, classes began on May 9 at the natural mathematics and technical faculties of the Turkestan People's University, which accepted Russians or Russian-speakers" (Kholboev, 2003, p. 70). It is interesting that no documents are required for admission, only the desire was enough.

In this way, the number of students admitted to the higher courses (faculties) of the People's University reached 1200 and 186 of them started studying at the technical faculty.

According to the archive data, there were 632 people who expressed their desire to study at the faculty. In fact, the number of regular participants in the lectures was very small and decreased sharply at the end of the semester. This is due to the lack of technical equipment, scientific and auxiliary rooms (scientific office, library, laboratories), and the fact that the existing buildings are not suitable for conducting university classes (NAUz (National Archive of Uzbekistan). F. R-34. D. 1. C. 107. S. 555).

Studying at the technical faculty will be four years instead of the usual five years, and it is planned to open sub-departments such as textiles and chemistry later. On May 9, 1918, according to the information about students at the technical faculty of the People's University, the number of electricians was 14 (NAUz (National Archive of Uzbekistan). F. R-368. D. 8. C. 1. S. 6).

Dean of the technical faculty A. Bykovn on June 17, 1918, wrote to the administration of Turkestan People's University, asking for an advance of 5,740 rubles to reward faculty employees and lecturers, and at the letter by June 18, 1918, informed in connection with the closing of the "General Electric Company" store, equipment costs for the purchase of equipment for the electrical laboratory at low prices were included in the faculty budget and according to the preliminary estimate, it was stated that the Council of the Faculty of Engineering approved the purchase of equipment in the amount of 11,000 rubles presented by the Board of Electromotive Courses, and a total of 22 types of equipment were requested (NAUz (National Archive of Uzbekistan). F. R-368. D. 8. C. 1. S. 33-34).

On June 18, 1918, the cost of the electrician course was 4,800 rubles. The project was reviewed and approved by the Technical Faculty Council. The courses were successfully conducted, and 50–70 regular listeners participated in them every day 2. Those who completed this course were tested by a separate commission, and only those who successfully passed received a certificate of completion of electrical installation courses (NAUz (National Archive of Uzbekistan). F. R-368. D. 8. C. 1. S. 3).

After listening to the information of the rector of the university A. V. Popov about the transformation of the technical faculty under the People's University into a form of higher education, the technical faculty of the collegium will remain within the People's University and in a short period of time, various courses will be combined into one whole – the People's Technical College, and it will be transferred from the university to the administrative training of the technical faculty and made a decision to transfer to the hands of persons of the organization who are not employed in the institution (NAUz (National Archive of Uzbekistan). F. R-34. D. 1. C. 38. S. 74).

According to the information of the commission for quality control of the students of technical faculty of the university, the origin of the students was also from different social classes (NAUz (National Archive of Uzbekistan). F. R-368. D. 8. C. 81. S. 10).

Table 4. Social classes of students of technical faculty of Turkestan People's University in Tashkent.

Level	Specialties' and governances' children	Servants', doctors' and layers' children	Intelligents' children	Unemployments' children	Craftsmans' children
1- course	8	18	1	1	1
2- course	4	7	-	-	-
3- course	2	5	-	2	-
4-course	-	-	-	-	1
Total	14	30	1	3	2

Conclusions.

The practical use of electric energy in the beginning of the 20th century, while the developing capitalist production demanded the creation of new energy bases, industrial production in Turkestan was in its infancy, and the colonial policy of the empire prevented the development of productive forces, the necessary conditions for the wider operation of the industry. was not available.

A lot of the proposals and projects for the construction of power stations in Tashkent were not implemented as a result of the neglect of the colonial administration in the country and the bureaucratic system. In many cases, disagreements over energy prices, difficulties in bringing technical equipment, lack of qualified personnel and the low level of the country's industrial sectors caused investors to abandon their plans. Although the number of power stations operating in the country increased somewhat on the eve of World War I and in during the war they were mostly used for the purpose of lighting buildings and streets of social importance, not industry.

The transport system in the country, first of all, the electrification of tram networks, was far behind the central districts of the empire, and the lack of financial resources for its development, changes in the political management system, and the world and civil war had a negative impact on the development of the sector. Nevertheless, Tashkent had the country's first electrified transport network, a status it maintained for decades to come.

The possibilities of the first higher education institution established in Tashkent during the studied period were limited, more Russians than local youths were educated in the field of electrical engineering. Due to the low monthly salaries of electrical engineers and workers, the lack of jobs, and unsatisfactory working conditions, many of them, who did not believe in the prospects of the network, made a living by hiring other jobs.

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Історія електрифікації Ташкента у 1914–1918 роках

Анотація. *Після колонізації регіону Туркестан Російською імперією в другій половині 19 століття, царські власті обрали місто Ташкент політичним, адміністративним та військовим центром усього регіону. Це було обумовлено передусім торгово-економічною перевагою Ташкента над іншими містами, а також його розташуванням у центральній частині країни та стратегічним значенням. Хоча промислові сектори були слабо розвинуті, розпочалися роботи зі створення електростанцій для освітлення міських вулиць та обслуговування малих виробничих підприємств. Основну увагу було приділено російському та іноземному капіталу, але початкові проекти не були реалізовані через бюрократичну систему. Хоча кількість електростанцій у Ташкенті зросла дещо в період 1914–1917 років, вони використовувалися лише для освітлення будівель та вулиць соціального значення, а не для промислових цілей. До 1914 року Російська імперія займала 8-е місце у світі за обсягом виробництва електричної енергії, з 14 кВт·год електрики на душу населення в центральних районах імперії, в той час як у Ташкенті цей показник складав лише 1 кВт·год на душу населення, що свідчить про те, що увага і основні інтереси метрополії були спрямовані на інші речі, а не на розвиток соціально-економічних секторів міста. Хоча участь Російської імперії в Першій світовій війні сприяла збільшенню виробництва в харчовій, текстильній та військовій промисловості, помітних змін в енергетичному секторі не відбулося. Зокрема, хоча в Ташкенті у 1914–1918 роках дещо збільшилася увага до будівництва електростанцій, фінансові труднощі для інвесторів та складні політичні зміни того часу негативно вплинули на кількість осіб, що були на чолі цих робіт, що призвело до відтермінування запланованих робіт. Економічно Ташкент та його околиці, як промислово-аграрний регіон, мали потенціал для впровадження різних інфраструктурних систем, мали великі природні ресурси сировини та всі умови для будівництва гідроелектростанцій, але ці природні можливості не були використані в повному обсязі.*

Ключові слова: *Ташкент; електрифікація; електростанція; контракт; лампа; трамвай*

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The rise of digital threats: A historical perspective on computer viruses and cybersecurity

***Abstract**. The rapid evolution of computer viruses has intensified the need for advanced detection mechanisms. This study examines the historical progression of malware and explores the role of machine learning in enhancing cybersecurity defenses. By analyzing major incidents, such as the Morris Worm, ILOVEYOU virus, and WannaCry ransomware, this research highlights patterns in malware development and the increasing sophistication of cyber threats. Findings reveal that traditional signature-based detection methods struggle to keep pace with evolving malware, necessitating a shift toward machine learning-based approaches. Techniques such as anomaly detection, behavioral analysis, and deep learning models have proven effective in identifying previously unseen threats. This study underscores how machine learning enhances real-time threat detection by recognizing subtle patterns and adapting to new attack strategies. Furthermore, the results highlight the challenges of adversarial attacks, where malware is designed to evade detection by manipulating input data. The study emphasizes the need for robust machine learning frameworks capable of resisting such threats. Additionally, integrating AI-driven models with traditional security measures has been shown to improve detection accuracy and response time. By leveraging historical insights and emerging technologies, this research advocates for a proactive approach to cybersecurity. The findings reinforce the importance of continuous advancements in machine learning-driven threat detection to counter increasingly sophisticated cyberattacks.*

Keywords: *machine learning-based detection; cybersecurity threats; anomaly detection; adversarial attacks; malware evolution*

Introduction.

The ever-growing reliance on technology has brought profound changes to modern society but also introduced vulnerabilities that pose significant risks. Computer viruses, once mere experimental tools for programmers, have evolved into sophisticated threats capable of disrupting critical systems, stealing sensitive information, and inflicting financial losses on a global scale (Benmalek, 2024; Sarkar & Shukla, 2023). The pressing issue lies in understanding the historical trajectory of these digital threats to anticipate and mitigate future challenges effectively. This study aims to trace the evolution of computer viruses and their corresponding cybersecurity measures, providing a comprehensive historical perspective that highlights key milestones and lessons learned.

To achieve this, the study adopts a qualitative approach, examining historical data and documented events to explore the motivations, mechanisms, and impacts of notable computer viruses. By employing a historical analysis framework, the study constructs a detailed timeline of these threats while assessing the development of defense strategies over time. Data sources include academic publications, news archives, and case studies that document pivotal incidents such as the Morris Worm, ILOVEYOU virus, and WannaCry ransomware. Through this method, the study unveils patterns that have shaped the cybersecurity landscape (Pärn, Ghadiminia, García De Soto, & Oti-Sarpong, 2024; Sanmorino & Kesuma, 2024). This study contributes to the field by offering a systematic understanding of how past experiences with computer viruses inform current and future cybersecurity practices. By analyzing the motivations behind these threats and the responses they elicited, the study not only highlights the importance of historical context but also provides actionable insights for enhancing digital defenses in an increasingly interconnected world.

The emergence of computer viruses dates back to the early days of computing, with initial examples serving as proof-of-concept experiments rather than malicious tools. For instance, the Creeper virus (1971) demonstrated self-replicating code, inspiring the creation of antivirus software (Ahmad, Bakar, Jan, & Yussof, 2024). Early viruses such as Brain (1986) and the Morris Worm (1988) revealed the potential for widespread disruption, signaling the need for proactive cybersecurity measures. Researchers have extensively documented these incidents, highlighting how the simplicity of early systems allowed relatively straightforward threats to gain global attention.

As the digital landscape evolved, so did the sophistication of viruses and their associated risks. The late 1990s and early 2000s witnessed the rise of viruses exploiting social engineering tactics, such as Melissa (1999) and ILOVEYOU (2000). These attacks demonstrated how human behavior could amplify a virus's reach and impact, leading to significant financial and operational disruptions (Dong, Wang, & Liao, 2016; Gulyás & Kiss, 2023). Scholars in cybersecurity have emphasized the pivotal role of email systems and user awareness in preventing such attacks, underlining the necessity of education alongside technological defenses.

Modern threats, exemplified by Stuxnet (2010) and WannaCry (2017), represent a paradigm shift in the use and purpose of malware (Allegretta, Siracusano, González, Gramaglia, & Caballero, 2025; Rose, Kabban, Graham, Henry, & Rondeau, 2025). These cases highlight the increasing use of viruses as tools for geopolitical and economic manipulation. Researchers have noted the growing complexity of malware, which now targets industrial systems, exploits zero-day vulnerabilities, and uses advanced evasion techniques. These developments underscore the critical need for collaboration between governments, industries, and researchers to build robust, adaptive cybersecurity frameworks capable of addressing these multifaceted challenges.

Literatur Review.

Existing Systematizations of Computer Viruses and Cybersecurity Evolution: The historical documentation of computer viruses and their corresponding defense mechanisms has been a subject of extensive study within cybersecurity research. Scholars have chronicled major cyber threats over the decades, identifying recurring patterns and technological adaptations (Benmalek, 2024; Sarkar & Shukla, 2023). Early studies primarily focused on cataloging prominent viruses, beginning with the self-replicating Creeper virus of 1971, which paved the way for modern malware analysis (Ahmad, Bakar, Jan, & Yussof, 2024). This foundational work established the basis for understanding how malicious programs exploit system vulnerabilities and human behavior to propagate.

As the field matured, researchers broadened their analyses, shifting from virus categorization to an examination of their societal and economic impact. Studies from the late 1990s and early 2000s explored the role of email-borne threats such as Melissa (1999) and ILOVEYOU (2000), demonstrating how social engineering techniques could amplify cyberattacks' reach (Dong, Wang, & Liao, 2016; Gulyás & Kiss, 2023). More recently, investigations into advanced persistent threats (APTs) and state-sponsored cyber warfare, particularly concerning cases like Stuxnet (2010) and WannaCry (2017), have underscored the evolving nature of malware from disruptive nuisances to sophisticated geopolitical tools (Allegretta, Siracusano, González, Gramaglia, & Caballero, 2025; Rose, Kabban, Graham, Henry, & Rondeau, 2025).

Gaps in Current Knowledge: Despite the extensive documentation of computer viruses, certain key gaps remain in the literature. First, while numerous studies have established virus timelines, there is a lack of in-depth analysis connecting historical malware evolution with present-day cybersecurity strategies. Existing research often treats virus development as a linear progression, overlooking the cyclical nature of cyber threats wherein past attack methods resurface in novel forms. This study addresses this gap by tracing historical patterns to better anticipate future cyber threats.

Another significant limitation in current research is the fragmented approach to studying cybersecurity responses. While technical advancements such as antivirus software, intrusion detection systems, and encryption protocols are well-documented, fewer studies comprehensively assess how organizations and governments have adapted to evolving threats over time. The role of global cooperation, regulatory frameworks, and public cybersecurity awareness remains underexplored, despite their increasing relevance in mitigating large-scale cyberattacks (Sanmorino & Kesuma, 2024).

Moreover, existing literature often underestimates the human factor in cybersecurity. While there is recognition of social engineering tactics in malware spread, the psychological and behavioral aspects of cyber hygiene—why users continue to fall victim to phishing emails or fail to update vulnerable systems—have not been sufficiently integrated into malware evolution studies. By incorporating an interdisciplinary perspective that includes human behavior, this study aims to bridge this research gap and offer a more holistic understanding of cybersecurity defense strategies.

Positioning This Work Within the Field: This study builds upon existing research by offering a historically grounded yet forward-looking analysis of computer viruses and cybersecurity. Unlike conventional studies that focus on either malware taxonomy or isolated case studies, this work synthesizes historical data with an analysis of cybersecurity measures to identify long-term patterns and vulnerabilities. By employing a historical analysis framework, this research contextualizes past cybersecurity failures and successes, offering insights that can inform contemporary digital defense strategies. Additionally, this study contributes to the growing discourse on adaptive cybersecurity, advocating for a shift from reactive measures to predictive defense mechanisms. Drawing on past incidents such as the Morris Worm (1988) and WannaCry (2017), this work illustrates how cybersecurity strategies must evolve to counter emerging threats proactively rather than retroactively (Pärn, Ghadiminia, García De Soto, & Oti-Sarpong, 2024; Karki, Hasan, & Sanin, 2024). By integrating technical analyses with behavioral insights, this study reinforces the argument that effective cybersecurity must be a blend of technology, policy, and user education.

In an era where cyber threats are increasingly sophisticated and interconnected, understanding historical cyberattacks is more than an academic exercise—it is a necessity for shaping future defense mechanisms. This study, therefore, serves as a critical bridge between past experiences and future cybersecurity innovations, offering a strategic perspective that policymakers, security professionals, and researchers can leverage to mitigate emerging digital threats.

Research Methods.

To explore *The Rise of Digital Threats: A Historical Perspective on Computer Viruses and Cybersecurity*, this study adopts a qualitative approach, drawing on historical data and documented events that have shaped the evolution of computer viruses and the corresponding cybersecurity measures. By analyzing past threats and responses, the study aims to provide valuable insights into the trajectory of digital security and the lessons learned along the way.

Approach: This research follows a historical analysis methodology, mapping the timeline of major computer viruses and the strategies developed to counter them. The study examines key malware incidents to understand their impact, motivations, and the countermeasures implemented. This method enables a comprehensive exploration of how cyber threats evolved and how security strategies adapted in response.

Selection Criteria for Viruses: The selection of viruses for this study is based on three key criteria:

Historical Significance – The virus must have played a pivotal role in shaping cybersecurity practices or technological advancements. For example, the Morris Worm (1988) led to the creation of CERTs, influencing global cybersecurity response frameworks.

Impact and Reach – The virus must have caused widespread disruption, financial losses, or institutional response. Notable examples include the ILOVEYOU virus (2000) and WannaCry ransomware (2017), which had significant global consequences.

Diversity in Attack Mechanisms – The study includes different types of malware (e.g., boot sector viruses, worms, ransomware) to illustrate the broad evolution of cyber threats and their adaptation to technological advancements.

Justification for Periodization: To provide a structured historical analysis, the study organizes the evolution of computer viruses into key periods:

Pre-Internet Era (1971-1985) – Viruses primarily existed in isolated environments, spreading through floppy disks and standalone systems.

Early Internet Age (1986-1999) – The rise of networked computers introduced faster-spreading threats, such as email-based macro viruses like Melissa (1999).

The Age of Sophisticated Cyber Threats (2000-2010) – Malware evolved with more destructive capabilities, including the politically charged Stuxnet (2010), demonstrating the potential for cyber warfare.

Modern Cybersecurity Challenges (2011-Present) – The emergence of ransomware, AI-powered attacks, and state-sponsored cyber threats, exemplified by WannaCry (2017) and advanced persistent threats (APTs).

This periodization provides a logical framework to understand how cybersecurity evolved alongside technological progress and digital connectivity.

Data Collection: The study relies on secondary data from multiple authoritative sources:

Books and Academic Papers – Historical accounts and technical analyses of malware.

News Archives and Reports – Documentation of significant cyber incidents, such as the ILOVEYOU and Stuxnet cases.

Technology Websites and Blogs – Insights from cybersecurity experts and organizations like Symantec, Kaspersky, and government agencies (Cartwright, Cartwright, & Edun, 2023; Cascavilla, Tamburri, & Van Den Heuvel, 2021).

Official Cybersecurity Reports – Publications from agencies like CERT, NIST, and industry white papers.

Analytical Framework: The collected data will be analyzed through a structured framework that includes:

Chronological Mapping – Organizing events into a structured timeline to highlight key developments in cyber threats and defenses.

Thematic Analysis – Identifying recurring themes such as motivations behind cyberattacks (e.g., financial gain, activism, espionage) and their impact on cybersecurity policies.

Comparative Analysis – Examining early and modern viruses to identify evolving attack patterns, prevention mechanisms, and industry responses (Chng, Lu, Kumar, & Yau, 2022; Irshad & Siddiqui, 2024).

Impact Assessment – Evaluating the broader consequences of major cyber incidents on regulatory policies, technological advancements, and public awareness.

Scope and Limitations: This study focuses on widely reported viruses and cybersecurity advancements, acknowledging that proprietary or unpublished data may introduce some limitations. Additionally, the study does not conduct primary investigations into malware but relies on credible secondary sources.

Expected Outcomes: This research aims to provide a historical overview of cyber threats, illustrating their impact on digital security practices. By tracing the evolution of computer viruses, the study sheds light on the ongoing cybersecurity challenges and the importance of adaptive security measures in the digital age.

Results and Discussion.

The Timeline of Major Computer Viruses.

The journey of computer viruses is a fascinating tale of creativity, chaos, and adaptation. From their humble beginnings as experiments in self-replicating code to becoming tools of global disruption (Kale, Bostancı, & Çelebi, 2024), computer viruses have evolved alongside the technology they target. Each significant virus in history tells a story—not just of technical ingenuity, but also of the changing motivations behind their creation, from pranks and protests to espionage and financial gain.

This timeline explores the key milestones in the evolution of computer viruses, shedding light on how these digital threats operated, the impact they had, and the lessons they taught us about cybersecurity (Fig 1). Through this historical lens, we can better understand the ongoing battle between malicious software and the defenses we build to protect ourselves in an increasingly connected world.

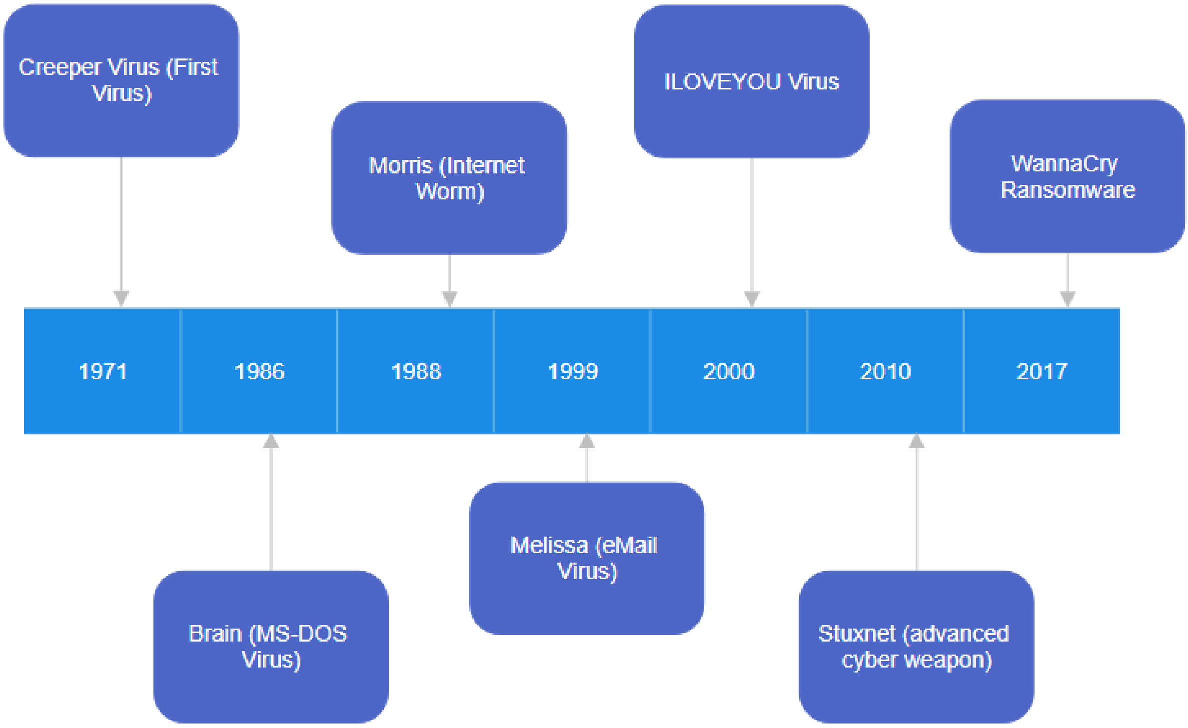

Figure 1. The timeline of major computer viruses (Authors' source).

Creeper Virus (1971): The Creeper virus was the first of its kind, designed not to harm but to demonstrate the concept of a self-replicating program. It worked by hopping between DEC PDP-10 computers running the TENEX operating system. Once it infected a system, it displayed a playful message:

"I'm the Creeper, catch me if you can!"

Instead of causing damage, Creeper replicated itself to other systems, leaving the previous one unharmed. This experiment inspired the creation of the first antivirus, called Reaper, which tracked and removed Creeper.

Brain (1986): Brain was the first MS-DOS virus, created by two brothers in Pakistan to protect their medical software from piracy. It spread by replacing the boot sector of floppy disks with its code, displaying a message with the creators' names and contact details. While Brain wasn't intentionally destructive, it slowed down infected systems and caused confusion, as users were unaware their disks had been altered. Its rapid spread via floppy disks demonstrated the potential of malware to affect systems globally.

Morris Worm (1988): The Morris Worm was the first major internet worm, designed by a computer scientist. It worked by exploiting vulnerabilities in Unix systems, including weak passwords and unpatched software. Once inside a system, the worm replicated itself and spread to other connected systems. Though not intended to cause harm, the worm's replication rate overwhelmed systems, slowing them down or crashing them. This incident highlighted the need for cybersecurity protocols and led to the establishment of the Computer Emergency Response Team (CERT).

Melissa Virus (1999): Melissa was a cleverly designed email virus. It arrived as an email attachment, often titled something enticing like "Important Message." Once opened, it unleashed a macro within a Word document that automatically sent the email to the first 50 contacts in the recipient's address book. Melissa's rapid spread disrupted email servers worldwide, forcing many companies to temporarily shut down their systems. It highlighted the dangers of malicious macros embedded in everyday documents.

ILOVEYOU Virus (2000): The ILOVEYOU virus took social engineering to the next level. It disguised itself as a love letter in an email, with the subject line "ILOVEYOU" and an attachment named "LOVE-LETTER-FOR-YOU.TXT.vbs." Users who opened the attachment activated a Visual Basic script that overwrote files, stole passwords, and spread itself to all email contacts. ILOVEYOU's combination of psychological manipulation and technical damage caused chaos, impacting millions of systems and resulting in billions of dollars in damages. It exposed the risks of opening suspicious attachments and the need for email security training.

Stuxnet (2010): Stuxnet was an advanced cyber weapon, designed to target industrial control systems. Unlike traditional viruses, Stuxnet infiltrated systems through USB drives and exploited multiple zero-day vulnerabilities. Once inside, it reprogrammed industrial equipment to malfunction, specifically sabotaging centrifuges used in uranium enrichment. Stuxnet's precision and stealth were revolutionary. It operated silently, causing physical damage without alerting users, and marked the dawn of malware being used as a tool for geopolitical objectives.

WannaCry Ransomware (2017): WannaCry was a ransomware attack that spread across the globe in hours. It used an exploit in unpatched versions of Microsoft Windows to gain access to systems, encrypting files and locking users out. Victims were shown a ransom note demanding payment to restore their data. The ransomware's rapid spread crippled hospitals, businesses, and public institutions, with damages exceeding $4 billion. WannaCry underscored the importance of timely software updates and the dangers of leaving systems vulnerable.

Table 1 provides a snapshot of some of the most notable computer viruses and malware in history, showcasing their diversity in type, the environments they targeted, and the impact they left behind. From the playful yet groundbreaking Creeper virus in 1971 to the devastating WannaCry ransomware attack in 2017, each entry reflects a turning point in the ever-evolving world of cybersecurity. These viruses not only caused financial losses and operational disruptions but also pushed the boundaries of innovation—on both sides of the cyber battlefield.

The evolution of computer viruses, as reflected in the table, highlights how their complexity and impact have grown over the decades. Early examples, such as the Creeper virus in 1971, were experimental and harmless, serving as a technical demonstration rather than a malicious threat. However, by the mid-1980s, viruses like Brain began exploiting vulnerabilities in floppy disks, marking the start of viruses spreading globally.

Table 1. The Most Notable Computer Viruses in History

Virus Name	Type	First Reported /Outbreak	Environment	Impact or Loss
Creeper	Experimental Virus	1971	Mainframe Computers	First proof-of-concept virus; no financial loss.
Brain	Boot Sector Virus	1986	PCs (Floppy Disks)	Slowed PCs; raised awareness of global virus spread.
Morris Worm	Internet Worm (Alanazi, Mahmood, & Chowdhury, 2023)	1988	Unix Systems	Caused system slowdowns and crashes; $10M in losses.
Melissa	Macro Virus (Rashid, Shafique, Akram, & Elagan, 2024)	1999	PCs (Email Systems)	Overloaded email servers; $80M in damages globally.
ILOVEYOU	Worm/Script Virus (Seshagiri, Vazhayil, & Sriram, 2016)	2000	PCs (Email Systems)	Overwrote files and spread rapidly; $10B in losses.
Stuxnet (Kumar, Govindaraj, Erturk, Nisar, & Inc, 2023)	Industrial Malware	2010	SCADA/ Industrial	Damaged Iran's nuclear facilities; geopolitical impact.
WannaCry (Evans & Purdy, 2023)	Ransomware	2017	PCs (Global Networks)	Crippled healthcare and businesses; $4B in damages.
Mydoom	Email Worm	2004	PCs (Email Systems)	Slowest internet speeds ever; $38B in economic losses.
Zeus	Trojan Malware (Kumar, Shersingh, Kumar, & Verma, 2024; Singh, Krishnan, Vazirani, Ravi, & Alsuhibany, 2024)	2007	Web (Banking Sites)	Stole financial data; billions in stolen funds.
Petya/ NotPetya (Gaber, Ahmed, & Janicke, 2025)	Ransomware	2016/2017	PCs (Corporate Systems)	Disrupted shipping/logistics; $10B in losses globally.

The Morris Worm in 1988 was a wake-up call for internet security, as it disrupted Unix systems and caused significant financial losses, showing the potential for widespread harm when networks were targeted. These early incidents underscored the need for more robust cybersecurity measures and led to the establishment of frameworks like CERT to mitigate future threats (Karki, Hasan, & Sanin, 2024; Kaur, Gabrijelčič, & Klobučar, 2023).

As technology advanced, so did the intent and scope of malicious programs. Viruses such as Melissa and ILOVEYOU in the late 1990s and early 2000s used email systems to propagate, demonstrating how social engineering could amplify their reach and damage. By the 2010s, the stakes were even higher with threats like Stuxnet and WannaCry. Stuxnet showcased malware's ability to physically disrupt critical infrastructure, highlighting its geopolitical implications, while WannaCry exploited network vulnerabilities on a global scale, causing billions in damages. These examples reveal a clear trend: viruses have moved from being curiosities to sophisticated tools capable of devastating financial, social, and political systems. This progression emphasizes the critical need for continuous innovation in cybersecurity to counteract ever-evolving threats.

Figure 2 shows the difference between the old virus mechanism and the modern virus mechanism in a flowchart.

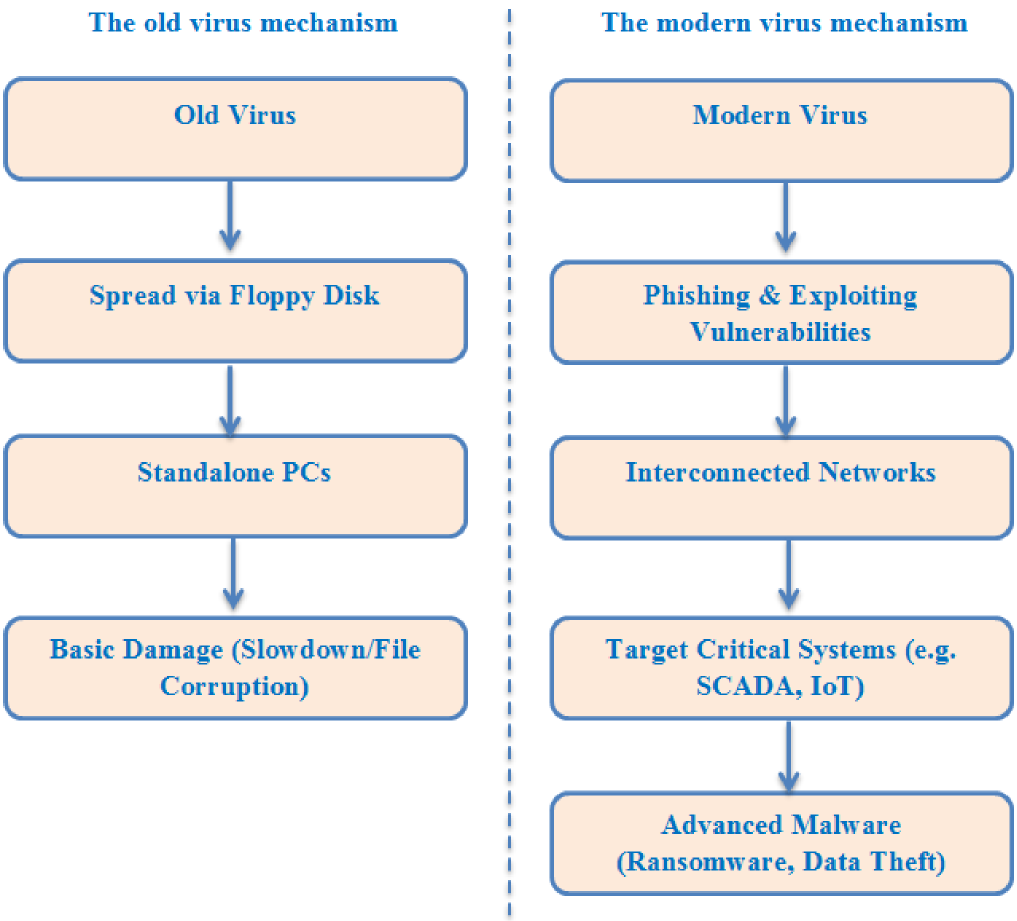

Figure 2. The virus mechanism (Authors' source).

The Figure 2 shows the evolution of computer viruses, contrasting the mechanisms of older viruses with those of modern malware. In the early days, viruses relied on simple distribution methods such as floppy disks. These viruses targeted standalone PCs and were often limited in their impact, causing minor disruptions like slowing down systems or corrupting files. Their functionality was straightforward, reflecting the limited connectivity and less sophisticated systems of that era. These early threats primarily served as proofs of concept or exploratory creations rather than tools for significant harm.

In contrast, modern viruses are far more complex and impactful. They exploit vulnerabilities in interconnected networks, often delivered through phishing attacks or malicious links. Modern malware targets critical infrastructure, including industrial systems and IoT devices, with devastating consequences (Ajay, Nagaraj, Arun Kumar, Suthana, & Ruth Keziah, 2024; Behera, Sahoo, Mishra, & Bhuyan, 2024). Advanced forms such as ransomware and data-theft tools aim for maximum financial or operational disruption, frequently affecting businesses and governments on a global scale. This shift demonstrates how the landscape of cybersecurity has transformed, requiring ever-more advanced defenses to combat these sophisticated threats.

The Virus Mechanisms.

The mechanisms of computer viruses have evolved significantly over time, moving from relatively simple self-replicating scripts to sophisticated cyberweapons capable of large-scale disruption. Understanding these mechanisms in detail—along with their quantitative impact—provides critical insights into their functionality, propagation, and mitigation strategies.

Infection Vectors and Propagation Methods: Viruses and malware spread through multiple mechanisms, each exploiting specific vulnerabilities within a system:

- **Boot Sector Infection** – Early viruses like Brain (1986) replaced the boot sector of floppy disks, altering system initialization. By embedding malicious code within the boot sector, these viruses ensured execution before the operating system loaded. Studies indicate that boot sector viruses affected 5–10% of computers in the late 1980s, particularly in environments with frequent floppy disk exchanges.
- **Email-Based Transmission** – Macro viruses like Melissa (1999) and ILOVEYOU (2000) utilized email attachments, exploiting the widespread use of Microsoft Word macros and Visual Basic scripts. Melissa alone infected an estimated 1 million computers within hours, causing over $80 million in damages. The ILOVEYOU virus escalated this technique, reaching 45 million machines worldwide and leading to an estimated $10 billion in financial losses.
- **Network Worms and Exploits** – The Morris Worm (1988) was among the first to exploit networking vulnerabilities, leveraging weak passwords and Unix sendmail flaws. Modern worms, such as WannaCry (2017), use remote code execution (RCE) exploits like EternalBlue (CVE-2017-0144) to infect

unpatched systems. WannaCry spread to over 200,000 computers in 150 countries within a day, causing $4 billion in damages.

Industrial Control System (ICS) Exploits – Stuxnet (2010) demonstrated the ability of malware to target programmable logic controllers (PLCs) in SCADA systems. The efficiency of Stuxnet's attack underscores how malware can manipulate cyber-physical systems to induce mechanical failures.

Payload Execution and Damage Mechanisms: Once inside a system, viruses deploy payloads with varied effects, categorized as follows:

System Overload and Denial-of-Service (DoS) – The Morris Worm's self-replication mechanism caused excessive CPU and memory usage, slowing systems and rendering them unusable. Modern botnets like Mirai (2016) leverage similar principles, weaponizing IoT devices to execute large-scale DoS attacks exceeding 1 Tbps in traffic volume.

Data Destruction and Manipulation – ILOVEYOU overwrote critical system files and personal documents. In contemporary attacks, ransomware like NotPetya (2017) encrypts entire disk volumes, utilizing AES-128 and RSA-2048 encryption schemes to make data recovery impossible without a decryption key.

Credential Theft and Espionage – Banking trojans such as Zeus (2007) use keylogging and form-grabbing techniques to steal user credentials. Zeus infected an estimated 3.6 million computers in the U.S., resulting in billions of dollars in stolen financial assets. Similarly, APT (Advanced Persistent Threat) malware like Pegasus (2016) exploits zero-day vulnerabilities in mobile devices to conduct state-sponsored surveillance.

Evolution of Defense Mechanisms: As malware sophistication increases, cybersecurity defenses must adapt. The following measures are critical in combating modern threats:

Behavioral-Based Detection Systems – Unlike signature-based antivirus programs, modern endpoint protection platforms (EPPs) use machine learning to identify anomalies. Research suggests that AI-driven malware detection achieves over 97% accuracy in distinguishing between benign and malicious files.

Zero Trust Architecture (ZTA) – Implementing ZTA minimizes unauthorized lateral movement within a network. This approach was instrumental in mitigating the spread of ransomware during the 2021 Colonial Pipeline attack, where network segmentation helped contain damage.

Regular Patch Management – Over 60% of ransomware infections exploit known vulnerabilities that remain unpatched. Organizations must enforce automated patching policies to reduce exposure to threats like WannaCry and EternalBlue.

Multifactor Authentication (MFA) and Least Privilege Access – MFA reduces the risk of credential theft, while least privilege policies limit an attacker's ability to escalate privileges within a compromised system.

Advanced Threat Intelligence and Incident Response – Real-time threat intelligence sharing through platforms like MITRE ATT&CK enhances proactive defense strategies, enabling organizations to anticipate and neutralize emerging threats.

The Motivations.

The motivations behind creating and spreading computer viruses have evolved significantly over time, reflecting changes in technology, societal dynamics, and individual intent. In the early days, many viruses were created out of curiosity or as experiments. As technology advanced and computers became integral to businesses and daily life, the motivations shifted to include financial gain, political activism, and even warfare. Some of the motivations behind viruses are as follows:

Pranks and Mischief: Early viruses were often created for fun or to showcase programming skills. The creators aimed to surprise or amuse others without causing severe damage. The Morris Worm (1988) caused disruptions but was more of an experiment than a malicious act.

Financial Gain: Many modern viruses are created to extort money or steal financial information, targeting businesses or individuals for profit. Ransomware like WannaCry (2017) demanded payments to unlock encrypted files.

Ideological Activism: Hacktivists use viruses to promote political agendas, raise awareness, or protest against organizations or governments. The Anonymous group and politically driven attacks on corporate or governmental networks.

Espionage: Viruses are often used by state-sponsored actors to steal sensitive data, conduct surveillance, or gain competitive advantages. Advanced Persistent Threats (APTs) like those targeting government and corporate secrets.

Sabotage: Malicious software may aim to disrupt critical infrastructure or operations, often for geopolitical or competitive reasons. Stuxnet (2010) was used to sabotage Iran's nuclear facilities.

Revenge: Individuals with grievances against organizations or people may use viruses to damage reputations or operations. Insider attacks involving malware planted by disgruntled employees.

Ego and Notoriety: Some hackers create viruses to gain recognition, prove their technical prowess, or demonstrate vulnerabilities in systems. Early creators like those of the Brain virus (1986) included their names in the code.

Research and Experimentation: Some viruses are created as experiments to understand vulnerabilities and develop stronger cybersecurity defenses. White-hat hackers and researchers sometimes release controlled viruses to test systems.

Accidental Creation: Occasionally, viruses are the unintended result of experiments or poorly designed programs that inadvertently cause harm. Early experimental viruses like Creeper (1971) were not designed to harm but ended up spreading.

Chaos and Destruction: Some creators are motivated purely by a desire to cause widespread disruption without any clear financial or ideological goal.

After learning about the various motivations behind computer viruses, the next step is to explain how to prevent, detect, and mitigate viruses. As the motivations and mechanisms of computer viruses have evolved, so too must our strategies for preventing, detecting, and mitigating them. While some timeless principles remain, the differences between old viruses and modern malware require us to adapt and refine our approaches.

Prevention.

Preventing old viruses was often simpler, as their spread relied on physical media like floppy disks or basic file transfers. The solution was straightforward: avoid using unverified disks, install basic antivirus software, and keep systems updated to close vulnerabilities. These practices were usually enough to thwart most early threats. Modern viruses, however, are far more cunning, often leveraging phishing emails, malicious links, and zero-day exploits. Preventing these requires advanced measures, such as deploying robust email filters, implementing strict patch management to close software loopholes, and educating users about recognizing social engineering tactics. Modern security tools like firewalls and endpoint protection suites further fortify systems against these sophisticated threats.

Detection and Mitigation.

Detection methods for old viruses typically involved scanning files for known virus signatures. These viruses were often repetitive and predictable, making signature-based detection reliable. Simple heuristic techniques also helped identify anomalies in files that had been altered by malware. Modern malware, in contrast, frequently evades traditional detection. Behavioral analysis tools monitor system activities to detect unusual patterns indicative of an attack, while machine learning-powered systems analyze large datasets to predict and identify evolving threats (Dey, Gupta, & Sahu, 2023; Sanmorino, Marnisah, & Kesuma, 2024). Network monitoring tools also play a critical role, scanning for unusual traffic patterns that might signal a breach or ransomware activity. Figure 3 shows the proposed network intrusion detection system (including malicious software, viruses, DDoS attacks, and malware) (Sanmorino, Marnisah, & Kesuma, 2024). The fine-tuned MLP model exhibited strong performance metrics with an average accuracy of 98.5%, precision of 98.1%, recall of 97.8%, and F1 score of 97.9%. These findings demonstrate the model's ability to distinguish between benign and malicious traffic, enhancing network security and resilience.

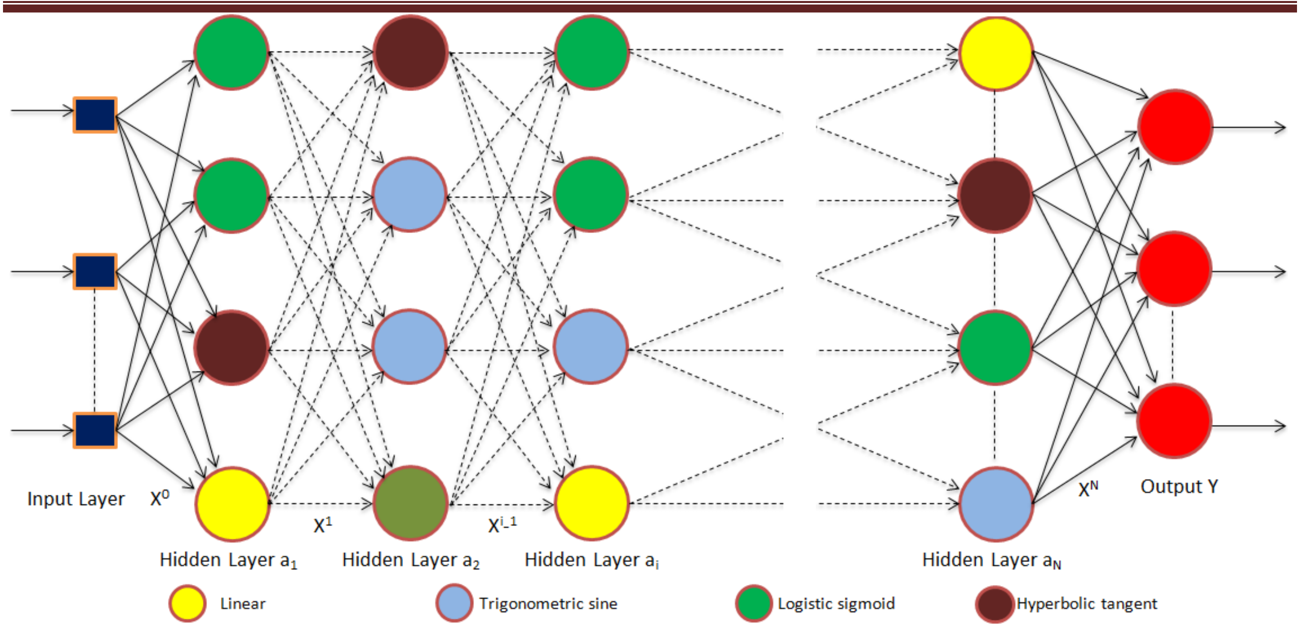

Figure 3. The MLP model architecture for network intrusion detection (Authors' source).

When it came to old viruses, mitigation was relatively straightforward. Infected files could be quarantined and deleted, and in severe cases, the operating system could be reinstalled. Backup systems often sufficed to recover overwritten or corrupted data. Modern viruses require a much more comprehensive approach. For instance, responding to a ransomware attack might involve isolating infected systems, leveraging secure offline backups, and, in some cases, deploying specialized decryption tools. Incident response plans have become essential, providing step-by-step actions to contain and neutralize threats quickly. Threat intelligence sharing with cybersecurity organizations helps mitigate large-scale attacks, ensuring a coordinated response. By understanding the unique characteristics of both old and modern viruses, we can see the importance of adapting our defenses to an ever-evolving landscape.

Future Viruses and AI.

The evolution of computer viruses is expected to accelerate with the integration of artificial intelligence (AI), making future cyber threats more intelligent, adaptive, and stealthy. AI-driven malware is no longer a hypothetical concept—current research and real-world cyberattacks already demonstrate how machine learning (ML) algorithms are being leveraged for malicious purposes (Kazimierczak, Habib, Chan, & Thanapattheerakul, 2024; Kritika, 2025; Sarker, Janicke, Mohsin, Gill, & Maglaras, 2024). As AI-powered cyber threats continue to evolve, understanding these advancements is crucial for cybersecurity professionals (Figure 4).

Initial Development: This is where cybercriminals create the foundation of the AI-powered virus. Using advanced programming, they embed AI algorithms into the malware. These algorithms enable the virus to think and act in a way that traditional malware cannot. Essentially, the virus is designed to learn, adapt, and operate independently, setting the stage for more sophisticated attacks.

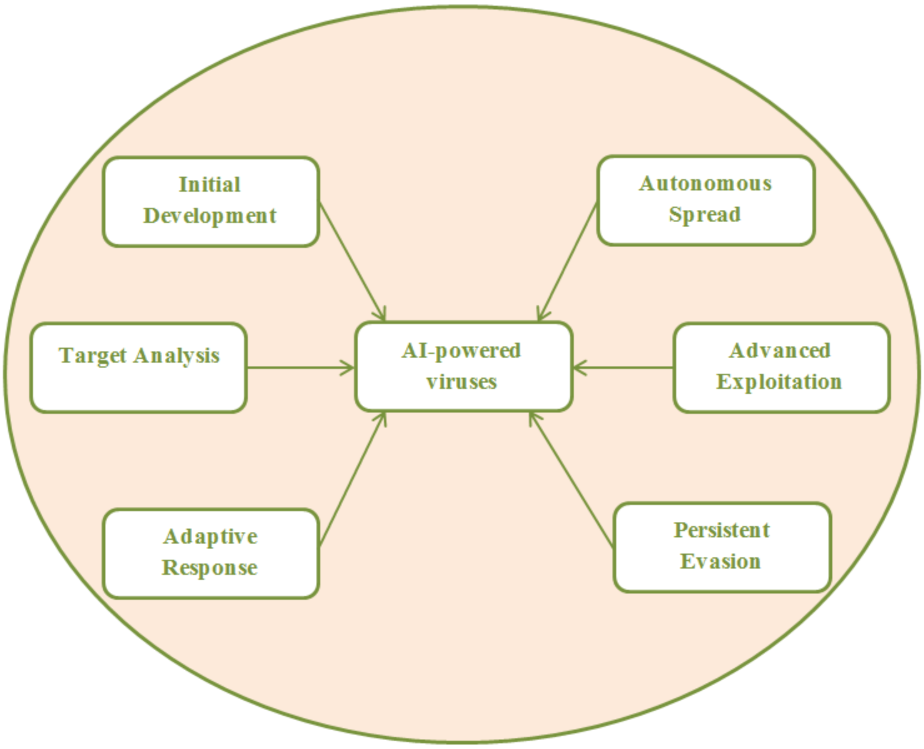

Figure 4. The future virus: AI-powered virus (Authors' source).

Target Analysis: Once deployed, the virus begins analyzing its environment. With AI's help, it gathers data on the target system, such as user behavior, system vulnerabilities, and network activity. For instance, it might observe when users typically access sensitive files or identify weak spots in outdated software. This data allows the virus to create a detailed profile of its target.

Adaptive Response: Here, the AI-powered virus showcases its intelligence. Based on the information gathered during target analysis, it adjusts its behavior dynamically. For example, if it detects that a firewall blocks a specific type of attack, it will shift to a different strategy. This adaptability makes it much harder for traditional security systems to keep up.

Autonomous Spread: Unlike older viruses that require manual triggers or straightforward scripts, AI-powered malware can propagate through networks on its own. It mimics legitimate traffic or activities, blending in to avoid raising suspicion. For instance, it might disguise itself as a regular system update or a harmless email attachment while spreading to connected devices.

Advanced Exploitation: Once inside the system, the virus leverages AI to exploit vulnerabilities with surgical precision. It might use zero-day exploits (previously unknown weaknesses in software) or tailor attacks to specific files, users, or applications. For example, in a corporate network, it could prioritize stealing financial records over less critical data.

Persistent Evasion: The final stage ensures the virus can stay undetected for as long as possible. The embedded AI constantly monitors security tools like antivirus software or intrusion detection systems (IDS). If it senses it's being analyzed, it adapts by encrypting its code, mimicking legitimate processes, or even deleting traces of itself to throw off defenders.

AI-Driven Attack Mechanisms.

Automated Malware Generation: AI-powered tools such as generative adversarial networks (GANs) have been shown to create highly polymorphic malware capable of continuously modifying its code to evade traditional antivirus detection. This technique was demonstrated in a study where GANs were used to generate malware that bypassed machine learning-based classifiers with a high success rate (Renjith, Sonia, Aji, Corrado, & Vinod, 2022).

Intelligent Target Analysis: AI-powered viruses can analyze massive datasets to identify system vulnerabilities, behavioral patterns, and weak points in network security. For example, the DeepLocker malware, developed as a proof-of-concept by IBM researchers, utilized deep learning to trigger its payload only when specific conditions were met—such as detecting a particular user's face via webcam or identifying specific geolocation markers.

Adaptive Evasion Techniques: Future viruses will employ adversarial machine learning techniques, such as data poisoning and model evasion, to bypass AI-driven cybersecurity defenses. Researchers have already demonstrated how malware can subtly alter its behavior to mislead intrusion detection systems (IDS). A notable example is the use of reinforcement learning to identify and exploit weaknesses in security models, allowing malware to adjust its tactics dynamically.

Autonomous Propagation and Execution: Unlike traditional malware that follows pre-programmed scripts, AI-enhanced viruses will use deep neural networks (DNNs) to autonomously navigate and spread across networks. They will mimic normal user behavior to avoid raising security alerts. The Emotet and TrickBot malware families already incorporate AI-driven techniques to analyze network environments and determine the most effective infection strategies.

Precision Exploitation of Zero-Day Vulnerabilities: AI-driven cyberattacks can leverage deep learning models to scan software for previously unknown vulnerabilities, commonly referred to as zero-day exploits. Researchers at Google's DeepMind have explored the use of AI for vulnerability detection, demonstrating that AI can identify flaws in software code more efficiently than traditional security teams. A real-world example is OpenAI's Codex model, which has shown proficiency in generating and modifying code—including potentially malicious exploits.

Persistent Evasion and Self-Healing Malware: AI-based malware will not only evade detection but also possess self-healing capabilities. By using AI-based mutation engines, future viruses could continuously rewrite portions of their code, preventing detection by behavioral analysis tools. The Houdini malware family has demonstrated early-stage AI-driven evasion by altering attack patterns based on security system responses.

The Potential Impact.

The impact of future viruses could be devastating. Businesses, governments, and individuals could face unprecedented levels of disruption. Imagine ransomware that not only encrypts data but also learns to target backups or AI systems that hijack decision-making processes in critical infrastructure like power grids or healthcare systems. Financial losses could skyrocket as cybercriminals become more efficient at exploiting vulnerabilities. The societal impact could also be profound. Trust in digital systems may erode if AI-powered viruses infiltrate essential services or manipulate information at scale. Cyberwarfare could escalate as nations deploy sophisticated malware against each other, potentially destabilizing geopolitical relations. Furthermore, individuals may face heightened risks to privacy, with viruses capable of harvesting and analyzing personal data in ways never seen before.

Preparing for the Future.

To prepare for this new wave of threats, cybersecurity must evolve alongside them. Organizations and individuals need to adopt proactive strategies that combine human ingenuity with AI-driven defenses. Advanced threat detection systems powered by machine learning will become indispensable, enabling real-time monitoring and analysis of network behavior to identify and neutralize emerging threats. Collaboration across industries and governments will also be crucial. Sharing threat intelligence and investing in cybersecurity research can help develop countermeasures before AI-powered viruses gain widespread traction. At an individual level, fostering a culture of cybersecurity awareness—such as understanding the risks of phishing and securing personal devices—will remain vital.

In essence, while the future of computer viruses will undoubtedly bring new challenges, it also offers opportunities to innovate and strengthen our defenses. By embracing cutting-edge technologies and fostering a united front against these threats, we can prepare for a safer digital future.

Contribution.

This study contributes to the existing body of knowledge by providing a comprehensive analysis of the impact of AI-powered threats on digital security. Unlike previous studies that primarily focused on traditional cyber threats, this research examines the evolving landscape of AI-driven attacks and the necessary countermeasures. Our findings highlight new vulnerabilities introduced by AI systems, emphasizing the need for adaptive security frameworks. Furthermore, we bridge the gap between historical security methodologies and modern AI-enhanced defense strategies. By comparing AI-powered threat vectors with traditional cyberattack patterns, this study offers valuable insights into the shifting nature of cybersecurity challenges. We also propose a predictive model leveraging machine learning techniques to identify emerging threats, improving response time and mitigation strategies. This research also contributes to policy development by outlining ethical considerations and regulatory measures necessary to address AI-powered cyber threats.

Conclusion.

As computer viruses continue to evolve, becoming more sophisticated and adaptive, our approach to cybersecurity must also advance. From early boot sector infections to AI-driven malware capable of autonomous decision-making, the landscape of digital threats has changed dramatically. Understanding the mechanisms, motivations, and potential impact of these evolving threats is crucial in shaping effective prevention, detection, and mitigation strategies. While modern cybersecurity tools leverage AI and machine learning to counteract emerging threats, the key to resilience lies in proactive defense measures, real-time threat intelligence, and collaboration among industries, researchers, and governments. As we move forward, the battle between cyber attackers and defenders will intensify, making continuous adaptation and innovation essential to safeguarding digital infrastructure and personal security in an increasingly connected world.

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Зростання цифрових загроз: Історичний погляд на комп'ютерні віруси та кібербезпеку

Анотація. *Стрімка еволюція комп'ютерних вірусів посилила необхідність у розробці передових механізмів виявлення загроз. Це дослідження розглядає історичний розвиток шкідливого програмного забезпечення та аналізує роль машинного навчання у вдосконаленні засобів кібербезпеки. Аналізуючи ключові інциденти, такі як хробак Морріса, вірус ILOVEYOU та програма-вимагач WannaCry, дослідження виявляє закономірності у розвитку шкідливих програм та зростаючу складність кіберзагроз. Результати показують, що традиційні методи виявлення, засновані на сигнатурах, не встигають за розвитком шкідливого програмного забезпечення, що зумовлює необхідність переходу до підходів, заснованих на машинному навчанні. Технології, такі як виявлення аномалій, поведінковий аналіз і моделі глибокого навчання, довели свою ефективність у розпізнаванні нових загроз. Це дослідження підкреслює, що машинне навчання підвищує ефективність виявлення загроз у реальному часі завдяки здатності розпізнавати тонкі закономірності та адаптуватися до нових стратегій атак. Крім того, результати висвітлюють виклики, пов'язані з атаками, що використовують методи протидії системам виявлення, коли шкідливе програмне забазпечення навмисно змінює вхідні дані, щоб уникнути розпізнавання. Дослідження наголошує на необхідності розробки стійких до таких атак машинних моделей. Також інтеграція моделей на основі штучного інтелекту з традиційними засобами кібербезпеки покращує точність виявлення загроз і швидкість реагування на них. Використовуючи історичні знання та новітні технології, це дослідження обґрунтовує необхідність проактивного підходу до кібербезпеки. Отримані результати підтверджують важливість безперервного вдосконалення методів виявлення загроз на основі машинного навчання для боротьби з дедалі складнішими кібератаками.*

Ключові слова: *виявлення на основі машинного навчання; загрози кібербезпеці; виявлення аномалій; атаки з використанням протидії; еволюція шкідливого програмного забезпечення*

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An interdisciplinary study of the effect of laser radiation on carbon fiber-reinforced polymer, in the context of counteracting unmanned aerial vehicles

Abstract. *This article presents an interdisciplinary study that combines historical analysis and experimental research to explore the vulnerability of military drones made from carbon fiber-reinforced polymer to destruction by laser radiation. The work is structured around two interconnected areas: the historical evolution of carbon fiber-reinforced polymer use in military drone construction and the parallel development of high-energy laser systems as precision countermeasures. The historical section traces the trajectory of carbon fiber composites from their initial applications in aerospace and defense industries during the late 20th century to their widespread adoption in military unmanned aerial vehicles, driven by the need for lightweight, durable, and radar-evading materials. Special attention is given to geopolitical, technological, and* *strategic factors that influenced the increasing reliance on carbon fiber-reinforced polymer for enhancing drone performance in terms of range, payload, and survivability. In parallel, the article examines the emergence of directed energy weapons, focusing on laser systems, as a response to the limitations of conventional kinetic countermeasures in neutralizing fast, small, and low-observable drones. The study outlines how the military's growing concern with swarm attacks and stealth unmanned aerial vehicles has accelerated investments in laser-based air defense systems capable of engaging airborne targets with high accuracy and low operational cost. The experimental component investigates the mechanisms of laser-induced damage in carbon fiber-reinforced polymer materials through controlled laboratory tests, during which samples are exposed to varying intensities and durations of laser radiation. The results are analyzed to determine the energy thresholds and exposure conditions that lead to effective material destruction. By synthesizing historical and experimental data, the article provides a comprehensive understanding of how past material choices have shaped current vulnerabilities in drone technology and how modern laser systems are specifically adapted to exploit those weaknesses. This integrated approach not only bridges the gap between history and applied science but also contributes to the development of more effective and informed counter-drone strategies in contemporary and future military operations.*

Keywords: *unmanned aerial vehicle; Counter Unmanned Aircraft Systems (C-UAS); laser weapon; carbon fiber-reinforced polymer; destruction*

Introduction.

Plastics and plastic composites based on polymers like polyethylene, polypropylene, PVC, PET, and epoxy resins are widely used across modern life due to their strength, flexibility, and cost-efficiency. They are found in packaging, automotive parts, electronics, construction materials, textiles, and medical equipment (Demchenko et al., 2022; Masiuchok et al., 2022). Composites reinforced with glass or carbon fibers offer enhanced mechanical performance, making them essential in aerospace, sports, and defense industries (Nugraha et al., 2022). Their versatility and adaptability have made them integral to industrial and consumer products alike. However, their extensive use also raises concerns over environmental sustainability, recycling challenges, and long-term ecological impact.

Carbon fiber-reinforced polymer (CFRP), commonly known as carbon fiber, has become increasingly popular in the design and production of military drones due to its superior performance characteristics that align with the tactical, operational, and strategic demands of modern warfare (Björck, Svedbrand, Sjöqvist, & Edström, 2022). One of the most critical factors is its exceptional strength-to-weight ratio, which enables military drones to carry larger payloads, such as advanced sensors, surveillance equipment, electronic warfare systems, or guided munitions, while maintaining lower overall mass. This lightweight yet strong material allows for extended flight durations, greater operational ranges, and improved fuel efficiency or battery endurance – key parameters in reconnaissance, surveillance, and combat missions. Carbon fiber's low radar cross-section is another decisive advantage in military contexts, as its non-metallic composition can reduce the radar visibility of drones, making them more difficult to detect by enemy defense systems and enhancing their stealth capabilities. Unlike metallic materials, CFRP does not reflect radar waves in the same way, making it highly suitable for the development of low-observable UAVs used in intelligence-gathering and strike operations in contested airspace (Allheily et al., 2016). Additionally, the structural rigidity and vibration-damping qualities of carbon fiber are critical in ensuring stable imagery and reliable operation of precision targeting systems, particularly during high-speed maneuvers or turbulent weather conditions. The resilience of CFRP under mechanical stress and its resistance to corrosion and fatigue under repeated cycles of load and environmental exposure further increase the durability and survivability of drones in harsh battlefield environments (Schäffer et al., 2024). From desert heat and coastal humidity to cold mountain climates, military drones often operate under extreme and variable conditions where conventional materials might degrade or fail; CFRP maintains performance integrity across these scenarios, reducing maintenance needs and increasing operational readiness. The flexibility of carbon fiber manufacturing techniques – such as custom molding and composite layup – also allows engineers to produce complex aerodynamic shapes that optimize lift, reduce drag, and enhance maneuverability, giving military UAVs an edge in speed, agility, and evasion. Moreover, CFRP enables the integration of embedded systems and components within the structure itself, including wiring channels, sensor housings, and even antennas, facilitating compact and streamlined designs that lower profile and improve mission adaptability. As military drones become increasingly modular and multifunctional – capable of switching roles from surveillance to strike or electronic warfare – CFRP supports rapid prototyping and reconfiguration. Cost efficiency is another emerging factor; while carbon fiber was once considered prohibitively expensive, advances in manufacturing and economies of scale have brought down costs, making it more feasible for defense applications where the performance return outweighs the investment. Lastly, as militaries invest in drone swarms and expendable UAVs, carbon fiber offers a balance between robustness and economic viability, allowing for high-performance platforms that are cost-effective even when deployed in high-risk or single-use scenarios. Taken together, these factors explain why carbon fiber-reinforced polymer has become a foundational material in military drone development, supporting not just structural efficiency but also stealth, resilience, adaptability, and advanced mission capabilities.

Lasers are deeply integrated into modern technology, with material processing being one of their most widespread and transformative applications. In industrial settings, lasers are used for high-precision cutting, welding, drilling, and marking of metals, plastics, ceramics, and composites (Shelyagin et al., 2005; Korzhyk et al., 2022; Lesyk et al., 2024). Their ability to deliver concentrated energy with minimal thermal distortion makes them ideal for producing clean, accurate cuts and joints in automotive, aerospace, and electronics manufacturing. Laser welding is increasingly favored for its speed and strength, especially in battery production and lightweight component assembly (Kumar, Tomashchuk, Jouvard, & Duband, 2024). In microelectronics and semiconductor industries, lasers enable delicate micromachining, surface texturing, and patterning at sub-micron scales. Additive manufacturing processes like selective laser sintering (Goncharuk, Zhuk, Kaglyak, Dzhemelinskyi, & Lesyk, 2018; Zavdoveev et al., 2022; Sokolovskyi & Bernatskyi, 2023) and direct metal laser sintering are revolutionizing the production of complex parts, reducing material waste and accelerating prototyping. Lasers are also widely used for surface treatments, such as hardening, annealing, and coating removal, extending the lifespan and performance of components (Berdnikova et al., 2021; Kritskiy et al., 2022). Beyond manufacturing, lasers play key roles in telecommunications, medicine, environmental sensing, and consumer electronics. In the military sphere, lasers are being developed and deployed as directed energy weapons capable of neutralizing drones, missiles, and other threats with precision and speed. Additionally, they are used for range finding, target designation, and optical communication in modern combat systems, enhancing accuracy and operational capability.

The current stage of development of countermeasures and means of destruction targeting military drones made of CFRP reflects a rapidly evolving intersection of material science, directed energy weapons, kinetic interceptors, and electronic warfare systems designed specifically to overcome the advantages offered by carbon-based composite materials. Carbon fiber, with its high strength-to-weight ratio, resistance to corrosion, and low radar visibility, presents a unique challenge to traditional anti-aircraft systems, prompting the development of more specialized counter-drone technologies. One major focus area is the advancement of directed energy weapons, particularly high-energy lasers, which are proving effective against CFRP drones due to their ability to induce rapid localized heating (Yang et al., 2020; Nallamalli, Singh, & Kumar, 2023; Schäffer, Wolfrum, Lueck, & Osterholz, 2024). Despite carbon fiber's high tensile strength and thermal tolerance, it remains vulnerable to concentrated laser exposure, which can cause resin matrix decomposition, delamination, and eventual structural failure. As a result, militaries and defense contractors are fine-tuning targeting algorithms to maintain precise beam focus on critical drone components – such as rotor arms or control surfaces – for long enough to achieve functional incapacitation, even at standoff distances. Similarly, microwave-based weapons are being adapted to exploit the carbon composite structure's potential weaknesses in shielding sensitive electronics; while CFRP is non-metallic and may not act as a conventional antenna, it often lacks the electromagnetic shielding capacity of metallic airframes, leaving embedded systems like GPS, flight controllers, and communication modules susceptible to directed electromagnetic pulses and high-powered microwave attacks. Concurrently, kinetic intercept systems are evolving to address the increased agility and reduced radar signature of carbon fiber drones. These include enhanced radar and infrared sensors capable of detecting low-observable

UAVs and guiding interceptor missiles or smart projectiles with improved terminal accuracy. Even conventional anti-aircraft guns are being upgraded with advanced fire control systems and proximity-fuzed ammunition to increase kill probability against fast, maneuverable, carbon-based drones. Another promising frontier involves drone-on-drone countermeasures, in which AI-guided interceptor UAVs physically ram or disable enemy drones mid-air, exploiting the lightweight, brittle nature of CFRP structures that are strong under tensile loads but vulnerable to concentrated mechanical impacts. At the same time, soft-kill approaches such as GPS spoofing, radio frequency jamming, and cyber intrusion continue to develop, taking advantage of the fact that, regardless of structural material, all drones rely on complex electronic systems to operate. While CFRP structures offer mechanical resilience, they provide no inherent defense against signal interference, making electronic warfare a highly effective, low-cost method to neutralize drones without requiring physical destruction. Research is also being directed toward material-specific sensors and tracking systems that can identify the distinct thermal or spectral signature of carbon fiber UAVs, which could support early warning and targeting for both defensive installations and mobile units. In parallel, the emergence of multi-layered drone defense systems – integrating radar, electro-optical sensors, electronic warfare suites, and rapid-response kinetic or laser weapons – is reshaping how militaries approach drone threats, particularly swarms of fast, low-flying UAVs constructed from CFRP (Björck, Svedbrand, Sjöqvist, & Edström, 2022; Taillandier et al., 2023; Schäffer et al., 2024).

Research Methods.

The methodology of this article is based on an interdisciplinary approach that integrates historical analysis with experimental studies to examine the development and destruction of military drones made of CFRP under laser radiation. The historical component involves a systematic study of the evolution of both CFRP materials in military aviation and the parallel development of directed energy weapons, with a focus on high-energy lasers (Bernatskyi, Lukashenko, Siora, & Sokolovskyi, 2024). Archival research will be conducted using military reports, defense industry publications, scientific journals, patent databases, and declassified documents to trace how and why CFRP became the preferred material in military drone construction, especially from the late Cold War period to the present. Particular attention will be paid to the influence of strategic doctrines, material science advancements, and the growing demand for stealth, agility, and endurance in unmanned aerial systems. In parallel, the study will analyze the military and technological motivations behind the development of laser weapons as a response to the increasing use of composite-material drones. The experimental part of the research will focus on the interaction between laser radiation and CFRP materials commonly used in drone manufacturing. Using controlled laboratory settings, CFRP samples will be exposed to high-energy laser beams under varying power levels, exposure times, and beam diameters. The results will help determine the thresholds at which laser radiation causes structural failure in carbon fiber composites. The integration of historical context with material testing will allow for a better understanding of how past choices in materials and military technology have shaped the current vulnerabilities and countermeasure strategies involving lasers. This combined methodology offers a dual lens – looking backward to trace the technological path that led to the current use of CFRP in drones, and looking forward to assess how laser-based systems exploit specific material weaknesses in modern warfare.

Results and Discussion.

Laser-Based Destruction of Military Drones Made from CFRP.

Laser-based destruction of military drones made from CFRP represents one of the most intensively researched frontiers in modern directed energy weapon (DEW) development (Figure 1), as militaries and defense agencies seek effective, precise, and scalable countermeasures to address the growing threat posed by stealthy, agile, and increasingly autonomous unmanned aerial systems (Schäffer et al., 2024).

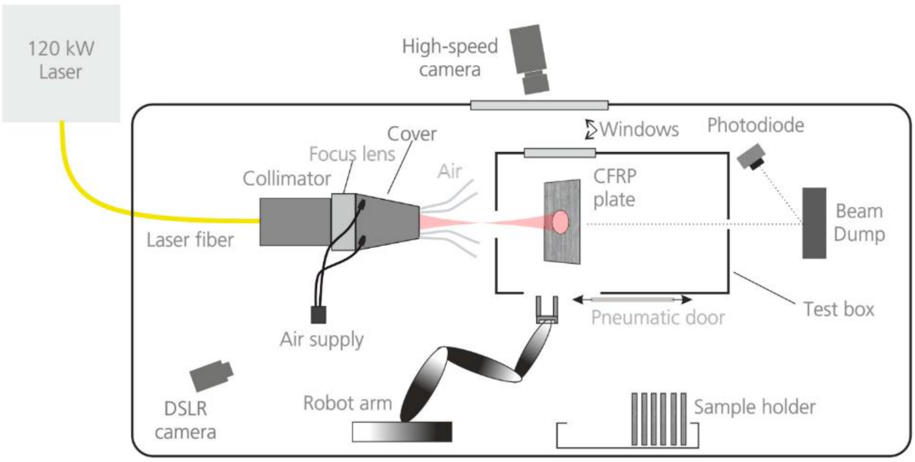

Figure 1. Experimental setup includes an automated sample exchange, operated by a robotic arm (Schäffer et al., 2024).

The interest i targeting CFRP drones with laser radiation arises from a unique intersection of the material properties of carbon composites and the operational characteristics of high-energy laser systems (Yang et al., 2020; Liao, Huang, & Xie, 2023; Taillandier, Regnault, Beaumadier, Beigbeder, & Pasquier, 2024). While CFRP is celebrated in drone design for its high strength-to-weight ratio, corrosion resistance, and reduced radar cross-section, it also possesses critical vulnerabilities – especially when exposed to sustained, high-intensity electromagnetic energy in the form of focused laser beams. Current research into laser-CFRP interactions is multifaceted (Figure 2), drawing from materials science, aerodynamics, optical engineering, thermomechanical modeling, and systems integration to determine optimal destruction strategies that can be deployed in real-world combat environments (Tresansky, Joyce, Radice, & Watkins, 2014; Taillandier et al., 2022).

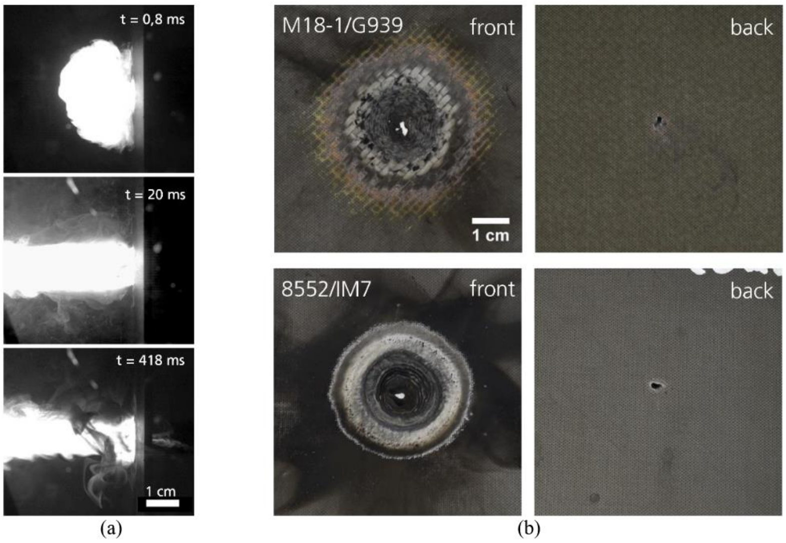

Figure 2. *(a)* Irradiation of CFRP with a laser power of 120 kW and a spot size of 20 mm results in an expanding gas cloud. The 4 mm thick CFRP plate is perforated after 0.4 seconds. *(b)* images of the damage zones on the front and back of irradiated CFRP samples made from two different fiber materials (Schäffer, Wolfrum, Lueck, & Osterholz, 2024).

One of the most fundamental aspects of this research is the study of thermal degradation mechanisms of CFRP under high-energy laser irradiation (Kujawinska, Kustron, Siedlecki, & Malesa, 2017; Schleijpen et al., 2020; Schäffer et al., 2024). Unlike metals, which typically melt under laser heating, CFRP materials undergo a more complex failure process due to their composite structure, which consists of carbon fibers embedded in a polymer matrix, usually an epoxy resin (Yang et al., 2020). When irradiated, the resin component absorbs laser energy and begins to thermally degrade at relatively low temperatures – around 300–400°C – causing delamination and decomposition, while the carbon fibers themselves can oxidize or structurally weaken at higher temperatures exceeding 600–1000°C. Researchers are investigating how different laser wavelengths, pulse durations, and power densities affect this failure sequence. For example, infrared lasers, particularly those in the 1.06–1.07 µm wavelength range (such as fiber lasers or Nd:YAG lasers), are often used due to their effectiveness in penetrating polymer layers and initiating thermal damage (Kim, Choi, & Kwon, 2024). Experiments have shown that with sufficient dwell time – i.e., the duration the laser beam remains fixed on a single point – CFRP components can be caused to structurally fail through a combination of matrix decomposition, fiber ablation, interlaminar cracking, and eventual rupture of load-bearing sections (Kujawinska, Kustron, Siedlecki, & Malesa, 2017).

In laboratory and field test environments, researchers are working to quantify the minimum energy thresholds required to defeat CFRP airframes under various atmospheric and operational conditions (see Figure 3). This includes accounting for heat diffusion in the material, the angle of incidence of the laser beam, and the rotation or movement of the target drone, which affects beam tracking and thermal coupling efficiency (Allheily et al., 2016; Zhang et al., 2018).

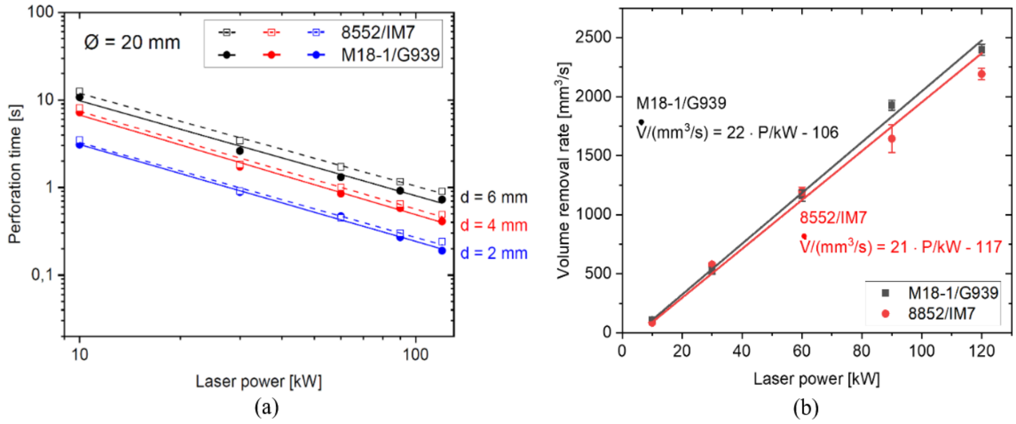

Figure 3. *(a)* Perforation times as a function of laser power in a double-logarithmic representation for CFRP plate thicknesses of 2–6 mm and a beam diameter of 20 mm. *(b)* Volume removal rate as a function of laser power (Schäffer, Wolfrum, Lueck, & Osterholz, 2024).

For example, studies have shown that targeting thinner structural elements – such as rotor arms, wing spars, or propeller hubs – requires less laser energy than attempting to destroy denser, more reinforced areas such as the fuselage or payload housing. One notable focus is on beam control systems that can stabilize and focus the laser on a rapidly moving, small-scale target at long range (Björck, Svedbrand, Sjöqvist, & Edström, 2022). Adaptive optics, real-time tracking algorithms, and gimbaled beam directors are being refined to enable high-precision engagements even against drones flying at high speeds, performing evasive maneuvers, or operating under variable weather conditions (e.g., wind, dust, fog, or rain, all of which can scatter or absorb laser energy).

Simultaneously, materials scientists are conducting extensive microstructural analyses – using scanning electron microscopy, thermogravimetric analysis, and infrared spectroscopy – to observe how CFRP deteriorates at microscopic levels under laser exposure (Kujawinska, Kustron, Siedlecki, & Malesa, 2017; Wolfrum, Eibl, Oeltjen, Osterholz, & Wickert, 2021). These analyses provide insights into how the interfacial bonding between the carbon fibers and polymer matrix behaves under sudden, localized thermal stress. The role of composite layup orientation, resin type, fiber weave, and even manufacturing imperfections such as voids or air gaps is being examined to identify structural configurations that are either more vulnerable or more resistant to laser damage. This information is vital for military planning, as it can inform targeting strategies (e.g., where to aim the laser for quickest disablement) as well as counter-countermeasures (e.g., what drone designs might resist DEWs better).

In the article (Wolfrum, Eibl, Oeltjen, Osterholz, & Wickert, 2021) SEM images also show that within the direct radiation zone the fibers and the matrix are burned or chipped off and a coneshaped perforation has developed (Figure 4).

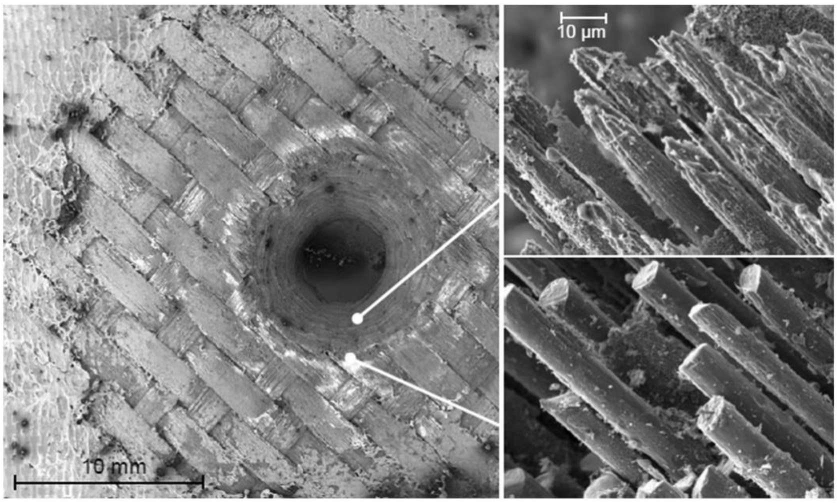

Figure 4. Scanning electron micrographs of a perforated 4 mm thick panel irradiated for 2.8 s (laser-spot-diameter: 10 mm; laser power: 5 kW), inserts show details inside and at the edge of the hole (Wolfrum, Eibl, Oeltjen, Osterholz, & Wickert, 2021).

Around the hole in the heat affected zone, the matrix has vanished on the front and back side of the panels, but the fibers are virtually undamaged (Wolfrum, Eibl, Oeltjen, Osterholz, & Wickert, 2021). A closer look at the edge of the hole on the front side reveals a typical shape of broken fibers with residual matrix particles sticking on them. This observation suggests that by the sudden heating at the beginning of the irradiation the material is predominantly chipped off. Video recordings of the laser tests confirm that smoke forms notably at the beginning of the tests due to the sudden thermally induced stresses (Figure 5).

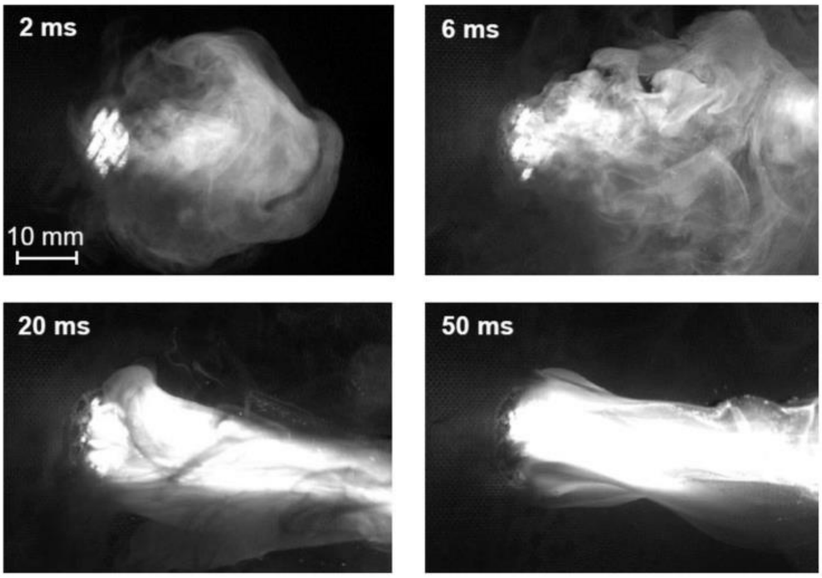

Figure 5. Images by a high-speed video camera showing different stages of the interaction of the high-power laser radiation with a 4 mm thick CFRP sample. (Laser power: 10 kW; Beam diameter: 10 mm; Perforation time: 1.2 s). (Wolfrum, Eibl, Oeltjen, Osterholz, & Wickert, 2021).

With increasing duration of the experiment, less chipping of fragments can be observed (Wolfrum, Eibl, Oeltjen, Osterholz, & Wickert, 2021). Then, oxidation processes additionally degrade matrix and fiber and less smoke forms. Inside the hole, the fibers look burned, the fiber ends are pointed and barely any matrix can be found on the fibers, both indicating that high temperatures have occurred. Additionally, the average carbon fiber diameter of initially 7.3±0.3 mm34 is reduced to 6.3±0.3 mm according to Figure 5 near the fiber ends and a rough surface structure of the fibers is observed. A decrease of the fiber diameter and the formation of surface defects are typical mechanisms of carbon fiber degradation in an oxidizing atmosphere. Thermal degradation of carbon fibers occurs beyond a minimum temperature of 650 °C in presence of oxygen, whereas the matrix degrades beyond ca. 300 °C within minutes. For the very short durations of the laser irradiation the temperatures are expected to be by far higher. A few small droplets probably are remains of melted glass fibers that are part of the M18-1/G939 material. In summary, the decomposition mechanism changes from chipping material to oxidizing it with increasing irradiation time and penetration depth. This finding specifies a report that theoxidative decomposition especially of carbon fibers does not occur, because formed pyrolysis products of the matrix hinders access of air. However, for prolonged laser treatment, ignition and oxidative decomposition occurr.

In parallel, computational modeling plays a major role in simulating laser-CFRP interactions (Tresansky, Joyce, Radice, & Watkins, 2014; Nan, Shen, Han, & Ni, 2019). Finite element models and computational fluid dynamics simulations are being used to predict heat transfer, material ablation, and structural failure modes under different laser exposure scenarios (see Figure 6).

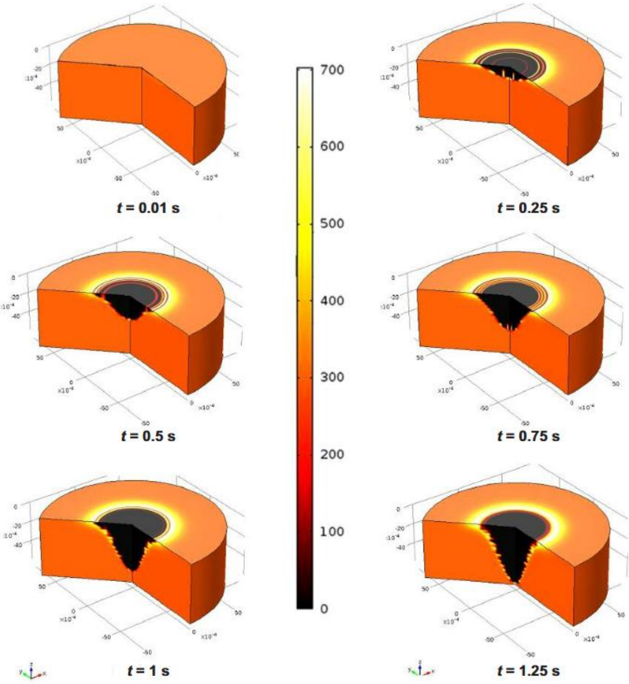

Figure 6. Computational modeling in simulating laser-CFRP interactions (Tresansky, Joyce, Radice, & Watkins, 2014).

These models are calibrated with experimental data and allow researchers to explore a vast range of variables – including different UAV geometries, composite thicknesses, and flight profiles – without the need for exhaustive physical testing. Such simulations are particularly important in military R&D contexts, where confidentiality, cost, and safety limit the scale of real-world trials. Moreover, these models are being integrated into software systems for use in operational laser weapon platforms, enabling real-time estimations of required dwell times and expected damage based on incoming drone specifications and environmental conditions (Nallamalli, Singh, & Kumar, 2023).

Another important area of research addresses the limitations of current laser systems against CFRP drones, particularly those designed for high-altitude or long-endurance missions (Björck, Svedbrand, Sjöqvist, & Edström, 2022). At high altitudes, for example, atmospheric density decreases, which can reduce laser absorption efficiency and beam coherence, thereby requiring more powerful or better-collimated lasers to maintain destructive energy densities. Additionally, some advanced drone designs incorporate ablative coatings or reflective surfaces to resist laser-induced damage, prompting counter-developments in multi-wavelength or pulsed laser systems capable of overcoming these defenses (Kujawinska, Kustron, Siedlecki, & Malesa, 2017). There is also growing attention to the thermal signature of drones during and after laser engagement; understanding how different CFRP configurations radiate heat can improve tracking and battle damage assessment capabilities, helping operators verify successful neutralization (Yang et al., 2020; Kim, Choi, & Kwon, 2024).

From a strategic perspective, militaries are increasingly viewing laser systems not just as tools for destruction, but as scalable platforms for layered defense against carbon-fiber-based UAVs. Low-power lasers may be used for disabling optical or infrared sensors, medium-power lasers for neutralizing propulsion systems or severing rotors, and high-power lasers for catastrophic structural failure (Allheily et al., 2016; Castrillo, Manco, Pascarella, & Gigante, 2022; Liao, Huang, & Xie, 2023). This layered approach aligns with the increasingly modular nature of both offensive drones and defensive energy weapons, allowing for tailored responses depending on the threat level, rules of engagement, or collateral risk. For example, in urban environments or near critical infrastructure, a precision laser strike that disables a CFRP drone without causing it to explode or crash uncontrollably may be preferable to kinetic interceptors or RF jamming techniques.

The current stage of applied research also includes extensive testing by defense agencies such as the U.S. Department of Defense, the Israeli Ministry of Defense, China's PLA, and NATO partners, all of whom are developing or deploying laser-based counter-UAV systems. Notable programs include the U.S. Army's DE M-SHORAD system, the U.S. Navy's LaWS (Laser Weapon System), Israel's Iron Beam, and Germany's HELWS initiative – all of which have demonstrated the ability to destroy or disable small drones made with composite materials, including CFRP. These systems aim for portability, rapid response times, and cost-efficiency per shot – since lasers operate using electrical power, they offer nearly unlimited "ammunition" compared to finite missile inventories. Such advantages are crucial as militaries confront increasingly frequent and diverse drone threats in asymmetric warfare scenarios.

Research into the destruction of CFRP-based military drones via laser radiation is in an advanced and fast-developing stage, with progress being made on multiple technical fronts – from materials science and beam control to targeting algorithms and thermal modeling (Tresansky, Joyce, Radice, & Watkins, 2014). While CFRP drones are formidable due to their lightweight durability and low observability, they are not impervious to well-targeted laser systems, especially when those systems are optimized for beam dwell, atmospheric correction, and material-specific engagement protocols (Björck, Svedbrand, Sjöqvist, & Edström, 2022). As laser technologies continue to mature and become integrated into mobile and fixed defense platforms, their role in neutralizing carbon-composite drones is set to expand significantly, reshaping the tactical landscape of drone warfare and accelerating the ongoing arms race between UAV innovation and counter-UAV lethality.

Experimental Study of the Effect of Laser Radiation on the CFRP & Discussion.

As part of the project "Study of the effect of a laser beam on the materials of UAV parts and substantiation of the technical parameters of the laser equipment of the mobile complex to combat them", the authors identified the materials most commonly used to make parts of various UAVs. In particular, it was found that parts of the hull of attack UAVs can be made of CFRP. This research was funded by the National Research Foundation of Ukraine under the project No. 2023.04/0166 " Study of the effect of a laser beam on the materials of UAV parts and substantiation of the technical parameters of the laser equipment of the mobile complex to combat them".

This part of the article is devoted to the study of the behavior of carbon fiber-reinforced polymer plate under the action of high-power laser radiation to determine the optimal parameters of destruction of this composite material (see Figure 7).

Figure 7. Example of the obtained results of the study of the effect of laser radiation on the carbon fiber-reinforced polymer plate (Authors' source).

The use of laser weapons against unmanned aerial vehicles made of carbon fiber-reinforced polymer is an urgent task, so the study of the effect of laser beam parameters, such as power, spot diameter, and angle of incidence, on the material destruction efficiency is of great practical importance.

For the experiments, we used a Nd:YAG laser with a radiation power of up to 4.4 kW and a wavelength of 1.06 µm. Carbon fiber-reinforced polymer sheets with dimensions of 1000 × 500 × 2 mm were laser processed with the variation of such parameters as power (1-4 kW), beam diameter (5-20 mm), angles of incidence (30°, 45°, 60°, 90°), and laser beam travel speed (0.5-2 m/min). Figures 8–11 show the results of these studies as angle of incidence 90°.

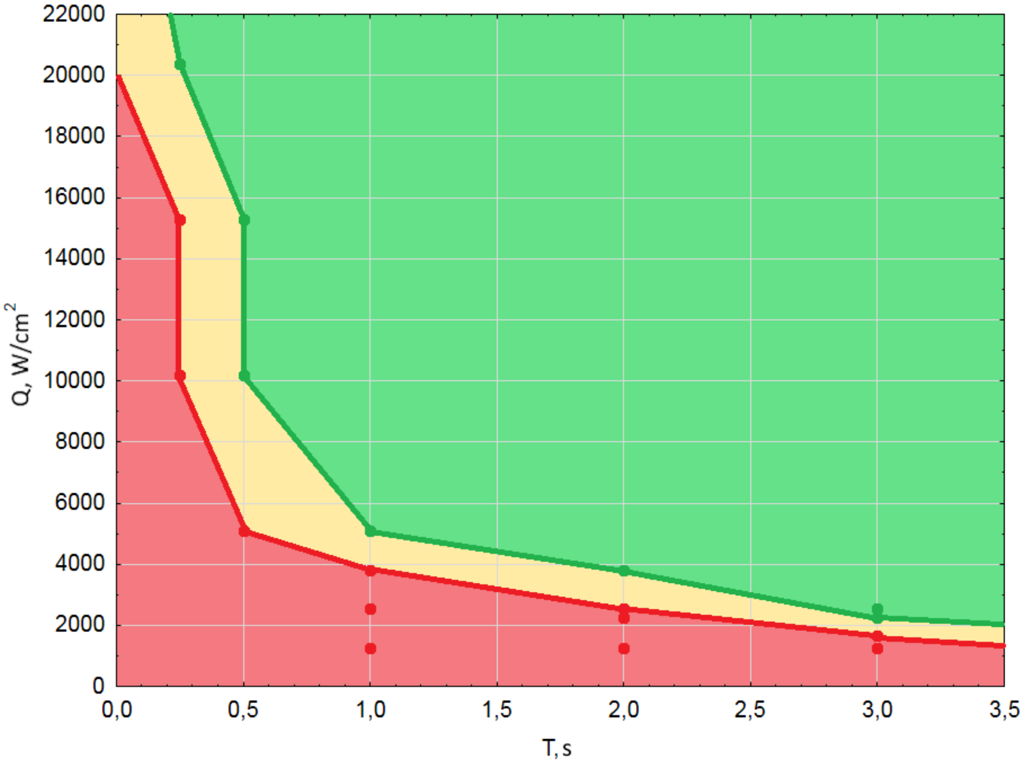

Figure 8. Graph of the effect of laser radiation on the penetration of a CFRP plate from power density as well as the exposure time.

The analysis of the data in this graph shows for penetration of a 2 mm thick CFRP plate, it is desirable to ensure a static exposure time of more than 0.5 s. The reason for this lies in the fact that during the laser treatment interval of 0.25-1 s, a 4x decrease in the laser power required to pierce the density is observed. It can also be noted that with an increase in the treatment time, the “uncertainty zone” (marked in yellow on the graph) decreases (see Figure 8).

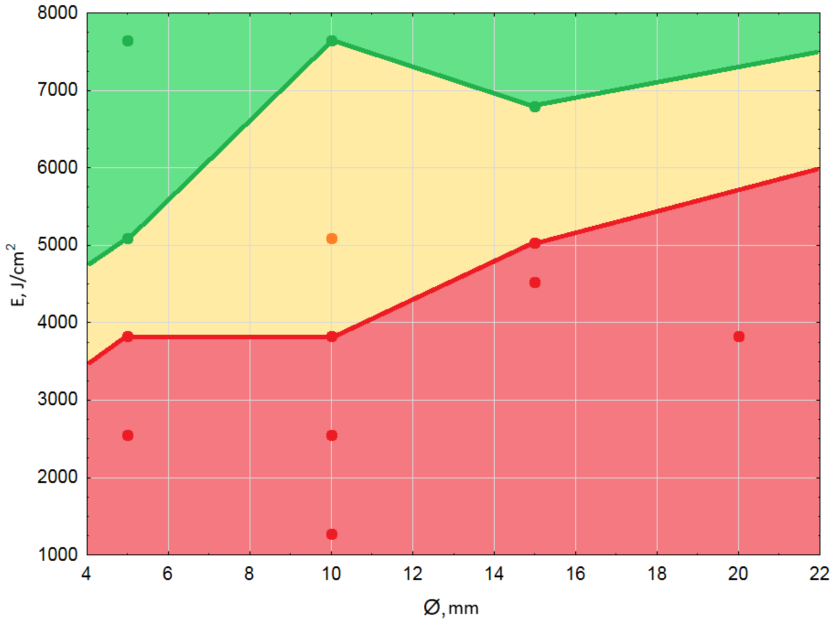

Figure 9. Diagram of the effect of laser radiation energy exposure and the diameter of the laser beam on the penetration of a CFRP plate.

The data shown in this graph indicate an increase in the energy exposure required to penetrate the carbon plate in proportion to the increase in the beam diameter (see Figure 9). This is attributed to a geometric increase in the beam cross-sectional area, which leads to a decrease in the laser power density. It is necessary to note the existence of an "uncertainty zone", in which cases with different processing results when using laser beams with identical energy exposure and beam diameter, exist due to the difference in the exposure time, which has a significant impact on the processing of this material.

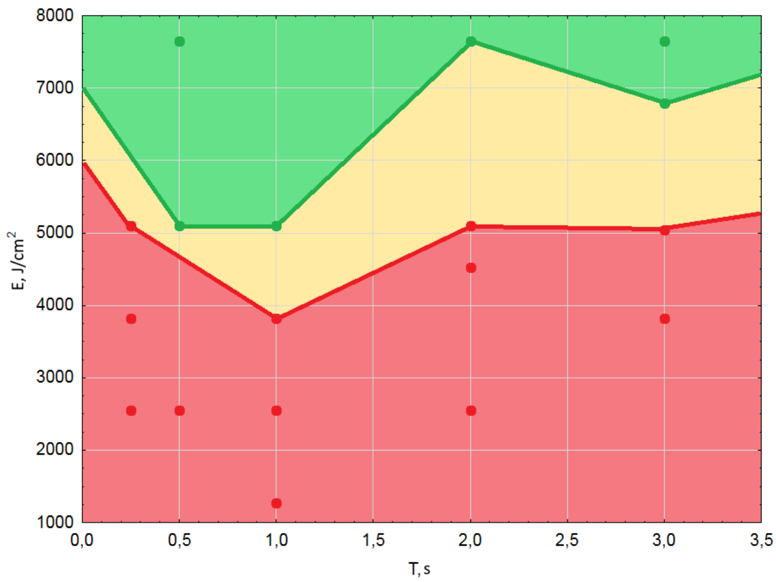

Figure 10. Diagram of the effect of laser radiation energy exposure and exposure time on the penetration of a CFRP plate.

The analysis of the data shown in Figure 10 shows that it is necessary to maintain the energy exposure at a level close to 5000 J/cm^2 to pierce a 2 mm thick CFRP plate. The anomaly, shown here is tied to the exposure time interval of 0.25–1 s, where the theoretically possible burn rate drops to 4000 J/cm^2. Despite this, this dependence holds for all other studied exposure time ranges.

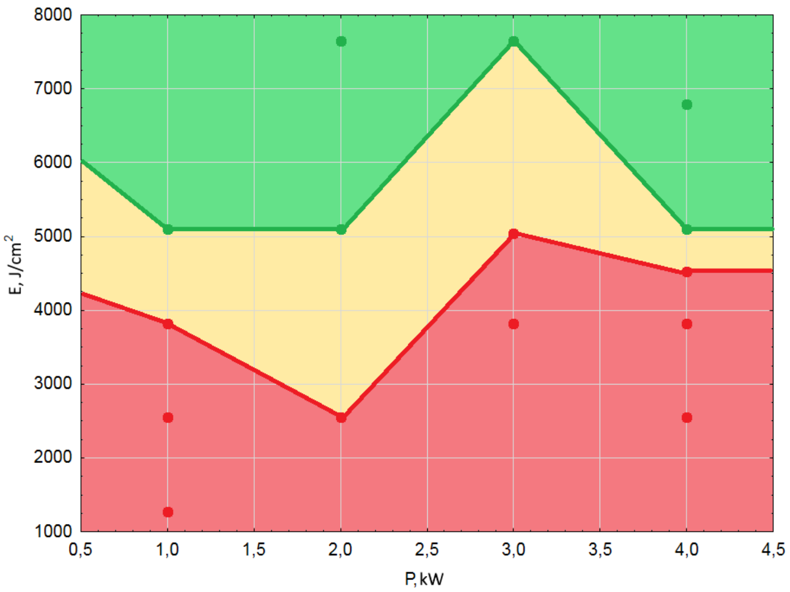

Figure 11. Diagram of the effect of laser radiation the energy exposure and laser power on the penetration of a CFRP plate.

This graph confirms the previously described principle, which states that in order to penetrate a plate of this material, it is necessary to ensure the energy component at a level above 5000 J/cm^2. A separate anomaly shown on this diagram is the guaranteed penetration point at 3 kW of laser power of 7644 J/cm^2, but the presence of an 'uncertainty zone' below this level is attributed to the lack of sufficient experimental data rather than an abnormal course of the penetration process at this laser power (see Figure 11).

The discussion of this interdisciplinary research reveals critical insights at the intersection of material science, military technology, and historical development, emphasizing how the strategic adoption of CFRP in drone design has created both technological advantages and new vulnerabilities – particularly in the face of modern laser weapon systems. Historically, the use of CFRP in military drones emerged in the late 20th century, initially within aerospace sectors such as the U.S. Department of Defense's stealth programs (e.g., the Lockheed Martin RQ-170 Sentinel), where lightweight and radar-absorbing materials were essential for reconnaissance in contested airspace. This trend accelerated in the early 2000s with the proliferation of medium and small tactical drones (e.g., MQ-9 Reaper, Bayraktar TB2), many of which employed CFRP in structural elements such as wings, fuselages, and rotor blades to enhance endurance, payload efficiency, and low observability. The advantages of CFRP – such as high tensile strength-to-weight ratio and corrosion resistance – made it a logical material for long-range, reusable aerial systems. However, this research demonstrates that these same properties do not guarantee resilience under directed energy attack, especially laser radiation.

From a historical and strategic viewpoint, these data suggest that the evolution of drone material design – originally intended to maximize stealth and endurance – has unintentionally created a target profile highly susceptible to thermomechanical damage under precision laser fire. The study highlights the paradox in contemporary drone warfare: as military UAVs have become more advanced, autonomous, and difficult to detect, they have also become more structurally vulnerable to compact, high-energy laser systems that can disable them with minimal collateral damage and low per-shot cost. This duality is important for defense planners considering both procurement and counter-UAV strategies. While the historical embrace of CFRP reflected a rational response to the tactical needs of the late Cold War and post-9/11 periods (e.g., intelligence, surveillance, and reconnaissance dominance, strike capabilities, and endurance), the present research implies that survivability in the age of directed energy weapons may require rethinking UAV material systems or incorporating additional shielding, modular repair features, or laser-deflective coatings. In conclusion, the interdisciplinary approach – drawing on historical context and laboratory experimentation – provides a deeper understanding of the vulnerabilities embedded in current drone design philosophy and underscores the need for next-generation solutions in both drone resilience and countermeasure sophistication.

Conclusions.

The integration of historical analysis and experimental investigation has proven to be an effective methodology for examining both the development and destruction of military drones made from CFRP when exposed to laser radiation.

Historical research reveals that the rise of CFRP as a dominant material in military drone construction was driven by a convergence of strategic doctrines, material science innovations, and increasing operational demands for stealth, endurance, and agility, particularly from the late Cold War era onward. The adoption of CFRP was not merely a technical preference but a strategic decision influenced by military needs for radar-evading platforms and reduced weight without compromising structural integrity.

The parallel development of high-energy laser systems was driven by the limitations of conventional kinetic weapons in countering modern drones. Lasers emerged as a precise and cost-effective solution to the challenges posed by fast, maneuverable, and low-observable UAVs constructed from composite materials.

Laboratory tests was funded by the National Research Foundation of Ukraine under the project No. 2023.04/0166, demonstrated that CFRP is vulnerable to laser radiation under specific power levels, durations, and beam profiles. These results establish critical thresholds for structural degradation and confirm that CFRP drones can be neutralized effectively with well-calibrated laser systems.

Funding.

This research was funded by the National Research Foundation of Ukraine under the project No. 2023.04/0166 "Study of the effect of a laser beam on the materials of UAV parts and substantiation of the technical parameters of the laser equipment of the mobile complex to combat them" (grant support No. 8/0166 dated March 03, 2025).

Conflicts of interest.

The authors declare no conflict of interest.

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Міждисциплінарне дослідження впливу лазерного випромінювання на полімер армований вуглецевим волокном, в контексті протидії безпілотним літальним апаратам

Анотація. *Ця стаття представляє міждисциплінарне дослідження, яке поєднує історичний аналіз та експериментальні дослідження для вивчення вразливості військових дронів, виготовлених з полімеру, армованого вуглецевим волокном, до руйнування лазерним випромінюванням. Робота структурована навколо двох взаємопов'язаних областей: історичної еволюції використання полімеру, армованого вуглецевим волокном, у будівництві військових дронів та паралельного розвитку високоенергетичних лазерних систем як високоточних контрзаходів. В історичному розділі простежується траєкторія розвитку композитів з вуглецевого волокна від їх початкового застосування в аерокосмічній та оборонній промисловості наприкінці 20 століття до їх широкого впровадження у військових безпілотних літальних апаратах, що було зумовлено потребою в легких, міцних та радіолокаційно-ізолюючих матеріалах. Особлива увага приділяється геополітичним, технологічним та стратегічним факторам, які вплинули на зростаючу залежність від полімеру, армованого вуглецевим волокном, для підвищення продуктивності дронів з точки зору дальності польоту, корисного навантаження та живучості. Паралельно у статті розглядається поява зброї спрямованої енергії, зосереджуючись на лазерних системах, як відповідь на обмеження звичайних кінетичних контрзаходів у нейтралізації швидких, малих та малопомітних дронів. У дослідженні окреслюється, як зростаюча стурбованість військових щодо ройових атак та малопомітних безпілотних літальних апаратів прискорила інвестиції в лазерні системи протиповітряної оборони, здатні вражати повітряні цілі з високою точністю та низькими експлуатаційними витратами. Експериментальний компонент досліджує механізми лазерного пошкодження в полімерних матеріалах, армованих вуглецевим волокном, за допомогою контрольованих лабораторних випробувань, під час яких зразки піддаються впливу лазерного випромінювання різної інтенсивності та тривалості. Результати аналізуються для визначення енергетичних порогів та умов впливу, що призводять до ефективного руйнування матеріалу. Синтезуючи історичні та експериментальні дані, стаття забезпечує всебічне розуміння того, як минулий вибір матеріалів сформував сучасні вразливості в технології дронів та як сучасні лазерні системи спеціально адаптовані для використання цих слабких місць. Цей інтегрований підхід не лише усуває розрив між історією та прикладною наукою, але й сприяє розробці більш ефективних та обґрунтованих стратегій боротьби з дронами в сучасних та майбутніх військових операціях.*

Ключові слова: *безпілотний літальний апарат; системи протидії безпілотним літальних апаратам (C-UAS); лазерна зброя; полімер армований вуглецевим волокном; деструкція*

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History of the all-welded Evgeny Paton Bridge

Abstract. *This article explores the history of science and technology through the lens of the design, fabrication, and long-term operational experience of the Evgeny Paton Bridge in Kyiv, the world's first all-welded highway bridge. Completed in 1953 and named after prominent welding pioneer Academician Evgeny Paton, the bridge represented a milestone in civil engineering and Soviet technological ambition during the postwar reconstruction era. The study examines the scientific and technical foundations that enabled the transition from riveted to welded structures, highlighting advances in metallurgy, structural analysis, and welding technology developed. It also considers the bridge's fabrication process, which involved large-scale application of automatic submerged arc welding and innovative solutions to challenges related to joint integrity, fatigue resistance, and thermal stresses. Drawing on archival materials, technical publications, and historical records, the article situates the bridge within broader political, institutional, and economic contexts, analyzing its role as both a functional infrastructure project and a symbol of Soviet scientific progress. The operational history of the bridge over more than seven decades is reviewed, emphasizing its structural resilience, maintenance practices, and the lessons learned that influenced later bridge engineering within the USSR and globally. It reflects on the interplay between scientific experimentation and practical engineering solutions, demonstrating how theoretical research was actively tested and validated through real-world implementation. The bridge's continued use into the 21st century provides a living laboratory for studying the long-term behavior of welded steel structures under dynamic loading and environmental stressors. In doing so, the article underscores the enduring relevance of historical technological achievements for current infrastructure policy, materials science, and engineering education. The Paton Bridge thus serves as a compelling case study in the evolution of large-scale welded construction and the ways in which technological innovation is embedded in broader historical narratives.*

Keywords*: history of bridge construction; history of metal bridges; welding history; Evgeny Paton Kyiv Bridge; engineering solutions; problems of maintenance and restoration*

Introduction.

Bridges are one of the most important elements of road infrastructure and one of the oldest inventions of mankind. As a rule, bridges consist of spans and piers. The spans are used to take loads and transfer them to the piers; they may contain a roadway, crosswalk, pipeline and so on. The piers transfer loads from the spans to the bridge foundation. Based on the purpose of bridges, it is logical to conclude that bridge structures operate under the most severe operating conditions. Therefore, the use of advanced technologies, including welding, determines the reliability and safety of the structure.

The first real metal bridge was built in the central industrial region of England, in the county of Shropshire across the river Severn (Sedmak, Ković, & Kirin, 2022).

At first, welding in bridge construction was not as resounding a success as in other industries (Strelko, 2023). The main doubts were caused by the reliability and serviceability of welded assemblies. The main arguments against the use of welding were based on the phenomenon of weld fatigue due to insufficient toughness of the welded material. Therefore, welding was initially used only in repair and restoration operations.

The transition from riveted joints to welded steel bridge structures has dramatically changed the practice of bridge construction. Welding in bridge construction started to be used as early as in the 30s. Its introduction was very cautious, and at the first stage it was supposed to make welded only factory departure blocks, and the assembly was to be carried out on rivets. This is how combined bridge structures appeared - welded with riveted assembly joints.

One of the most famous welded bridges is the Kyiv Evgeny Paton Bridge. It is one of the bridges over the Dnipro River in the capital of Ukraine in the city of Kyiv. The bridge is named in honor of academician Eugene Oskarovich Paton, who was its author of the idea, initiator of development and chief designer. When designing the bridge, E. O. Paton for the first time proposed to use modern technology − electric welding instead of riveted joints in the installation of the main girder purlins. The engineer's innovation had not been tested anywhere before, and therefore caused resentment of his colleagues and displeasure of his superiors. However, the scientist still managed to get his idea for electric welding applied.

Researching the design and construction of the all-welded Evgeny Paton Bridge in Kyiv from the perspective of the history of science and technology requires posing a series of critical and interrelated questions that explore both the technical and socio-political dimensions of this landmark engineering achievement. First, it is essential to ask: what were the specific scientific and engineering innovations that made the construction of the world’s first all-welded bridge possible, and how did these reflect the state of materials science, structural mechanics, and welding technology in the Soviet Union during the mid-20th century? Closely related is the question of how the bridge's design process integrated contemporary knowledge about fatigue resistance, thermal effects, and stress distribution in welded joints, and to what extent this knowledge was based on theoretical research versus empirical experimentation. Another important question involves the institutional and political context: how did the broader goals of Soviet industrialization, scientific advancement, and ideological emphasis on technological leadership shape the decision to build an all-welded bridge, and what role did government agencies, academic institutions, and key figures like Evgeny Paton play in promoting and legitimizing the project? Furthermore, it is necessary to ask how the bridge's construction methods and materials were selected, tested, and scaled, and what logistical and technological challenges had to be overcome in the absence of extensive precedent. The role of labor and expertise also warrants attention: what kinds of training, skillsets, and organizational systems were required to implement large-scale industrial welding on a civil engineering project of this magnitude, and how was knowledge shared or developed on site? Finally, a critical historical inquiry should examine how the Evgeny Paton Bridge influenced subsequent developments in bridge engineering, both within the Soviet Union and internationally, and how it was represented in media, scientific discourse, and public narratives as a symbol of modernity, national pride, and technological innovation.

Getting answers to the above questions was the purpose of this article.

Research Methodology.

Researching the design and construction of all-welded bridges is of profound importance from the perspective of studying the history of science and technology, as it illuminates a transformative moment in engineering practice that reflects broader industrial, technological, and societal shifts throughout the 20th century. The emergence of all-welded bridge construction signified not merely a change in technique but a paradigm shift in structural engineering philosophy, influenced by the interplay of scientific discovery, wartime necessity, industrial capabilities, and evolving transportation demands. Unlike riveted bridges, which relied on thousands of mechanically fastened joints, all-welded bridges introduced the concept of seamless load transfer, enabled by the science of metallurgy and the practical mastery of welding technologies. This innovation reduced material use, lowered dead loads, and simplified fabrication processes – yet it also posed new challenges, especially in understanding the fatigue behavior of welds, the properties of heat-affected zones, and the need for precise control during construction. The decision to transition toward all-welded structures was not made in isolation; it was grounded in advances in welding science – particularly arc welding – and a growing body of empirical research supported by academic institutions, government bodies, and engineering firms. For historians of science and technology, tracing this evolution provides insights into how scientific principles were translated into real-world applications, reshaping the built environment in ways that remain consequential today.

Studying the development of all-welded bridges also offers a window into the socio-economic and political contexts that drive technological innovation. For example, during and after *World War II*, the urgent demand for rapid infrastructure development, combined with labor shortages and material constraints, encouraged the adoption of more efficient, mechanized fabrication methods, among which welding was paramount. Welding technology, initially developed and refined for shipbuilding and armament production, found new peacetime applications in civil engineering – most notably in bridge construction. Furthermore, this transition required engineers to challenge and rethink traditional design norms, leading to the creation of new calculation methods, stress analysis models, and safety factors specifically tailored to welded structures. Such advancements highlight the dynamic interplay between theoretical knowledge and practical engineering, a core focus within the history of technology.

In addition, research into the design of all-welded bridges reveals how professional institutions, codes, and standards evolved in response to both successes and failures. Notable bridge collapses or structural issues due to fatigue cracking in welded joints during the mid-20th century served as catalysts for intensive investigation into fracture mechanics and material fatigue – topics that were still emerging in the scientific discourse. These incidents led to more conservative design approaches, rigorous inspection protocols, and international collaboration on welding standards, such as those developed by the American Welding Society or the International Institute of Welding. Historians of science and technology can explore how such feedback loops between practice and regulation influenced the broader discipline of structural engineering, shifting it from an empirical art to a more scientifically grounded profession. This evolution also demonstrates the role of failure as a driver of scientific advancement, illustrating how knowledge systems are shaped by real-world testing and recalibration.

Moreover, the study of all-welded bridges highlights the globalization of engineering knowledge. As countries rebuilt after *World War II* and entered periods of rapid modernization, the techniques and philosophies behind all-welded bridge construction spread across continents. Engineers from different cultural and educational backgrounds began to collaborate, sharing insights through international journals, conferences, and technical exchanges. In this sense, all-welded bridge construction serves as an example of "technological diffusion" – a process by which innovations are transmitted, adapted, and localized across borders. This phenomenon provides rich material for historians interested in how technologies travel and transform, influenced by regional needs, material availability, labor practices, and climate conditions. For instance, the adaptation of welding techniques for tropical climates or seismically active regions required modifications to design practices, welding materials, and inspection protocols, which in turn stimulated new research and innovation.

Furthermore, exploring the history of all-welded bridges underscores the intersection of human skill, machine capability, and scientific knowledge. Welding, unlike purely mechanized processes, remains a craft that demands precision, training, and tacit knowledge – especially when performed in challenging environments such as over rivers, in high winds, or on large-scale structures. The role of the welder, often overlooked in historical narratives, becomes central in this context. Oral histories, trade manuals, and training programs from the mid-20th century offer rich primary sources that reveal how this expertise was cultivated, transmitted, and institutionalized. From the perspective of science and technology studies, such research emphasizes the importance of human agency and the embodied knowledge that underpins even the most "technologically advanced" systems. It challenges deterministic views of technological progress by showing how real-world implementation depends on a blend of theoretical understanding and skilled labor.

Results and Discussion.

Idea. Justification. Scientific Research Underlying the Development.

In 1929, E. O. Paton decided to use welding instead of riveting in bridge construction. He shares his impression of the first time he saw the work of a welder: "The external simplicity of welding, the ease and ease with which the holder was operated by a young worker on the bridge, gave me an idea of welding as something very uncomplicated... It often happens like this: as long as a person is a novice in something new to him, as long as he looks only from the outside, everything seems clear, accessible and simple to him. So it was with me" (Paton, 1956, p. 103).

Single attempts in building welded bridges had so far failed (Poznyakov, Dyadin, Davydov, & Dmytrienko, 2021). That fact was first of all associated with a sharp drop in the load-carrying capacity of welded joints during manufacture of large-sized metal structures. The main cause for such a drop was a simple replacement of riveted joints on welded ones without taking into account the stressed state of welded elements and imperfection of welding technologies developed at the time, which led to crack formation both during manufacture (shop and site welding), as well as during operation of welded structures. Brittle fractures of welded structures in the 1940s began to bear a mass character, the majority of which had a number of features:

- fracture nuclei were usually located at the places of welded joints;
- fracturing occurred at very low operating loads and relatively high temperatures;
- a number of partial fractures of welded structures significantly increased.

As early as in the 30's by the works of E. O. Paton and B. N. Gorbunov in the E. O. Paton ElectricWelding Institute of the Academy of Sciences of the UkrSSR (PEWI) proved that it is most rational to use butt welded joints for structures operated under static and vibration loads, as they provide minimum stress concentration (Paton & Gorbunov, 1933). However, these conclusions of scientists were not used by designers for a long time due to the ingrained design methods of riveted structures.

The quality of welded bridge spans was low, and the steel itself had a high threshold of cold resistance. There were many deficiencies in the truss design, the main one being overlapped or overlapped joints. This resulted in a large accumulation of flank and lob joints in some places of the trusses, which caused high residual stresses from welding, contributing, in combination with the poor quality of welding and the selected steel, to the formation of cracks in the truss elements during installation and operation. This led a number of specialists and generally design organizations to strongly oppose the use of welding in railway and road bridges. As a result, on the eve of the *World War II* the rate of welded bridge construction in the USSR sharply decreased. During 10 years (1931–1942) only 28 welded spans weighing about 1,500 tons were built in the USSR.

However, welded bridge construction also had ardent supporters. First of all, E. O. Paton belongs to them. Foreseeing a great future for welded bridges, he continued with unflagging energy to study the problems of welded bridge construction. Researchers paid much attention to the study of the operation of combined rivet-welded joints as applied to bridge truss assemblies, longitudinal and transverse roadway girders with bond attachments. At the PEWI, E. O. Paton and V. V. Shevernytskyi (Paton & Shevernytskyi, 1948a; 1948b) have established the locations of destructive forces in the combined connection, in the connection with rivets, and also in the connection with welded seams. The properties of "welding steel" melted in puddling furnaces and used in old bridges were studied for this problem. Due to the lack of ductility of this steel and delamination, brittle fractures often occurred (Paton & Shevernytskyi, 1949).

Large experimental works on comparing the serviceability of welded and riveted trusses were carried out by E. O. Paton and B. N. Gorbunov (Paton & Gorbunov, 1935; Paton, Gorbunov, & Bershtein, 1937; Gorbunov, 1941). In tests of riveted and welded trusses with a span of 12 m, loosening of rivets was observed after 30 thousand loads, failure of welded and riveted trusses - after 230–250 thousand loads.

In 1940, when considering the construction project of a new road bridge over the Dnipro River in Kyiv, E. O. Paton proposed to apply the method of automatic submerged-arc welding for the manufacture of its elements. The Kyiv highway bridge was to be the first bridge in the world welded by automatic welding machines. Since it was very difficult to ensure the proper quality of seams at the construction site at that time, it was decided that all welding work should be done at the Babushkin Dnepropetrovsk Metal Construction Plant, and the assembly joints should be riveted. Within a month the design bureau of the PEWI developed a project and working drawings of the welding bench and chain turner to it. By the beginning of the war a considerable part of the structures was manufactured by the plant, two spans were delivered to Kyiv and one of them was assembled, seven spans remained at the plant. This metal was used in 1944 in the restoration of the Dnepropetrovsk bridge over the Dnipro River.

The question of construction of motor-road bridge in Kyiv across the Dnipro river was raised before the *World War II* (Lobanov & Kyrian, 2013). By that time the technical project of the bridge with driving atop and split through main truss girders, covering the spans of 58 m length (in the floodplain part) and 87 m (in the navigable one) was drawn up and approved. As in that period at the PEWI the method of automatic submerged arc welding was developed allowing the producing of high-quality welds, E. O. Paton proposed to manufacture spans of the bridge using welding.

And then, the opponents of application of welding in bridge construction raised their swelled heads over (Glavmostostroy, Leningrad Research Institute of Bridges, Glavstalkonstruktsiya, Ministry of Railways). At the meeting they stood up for the technology of riveting of bridges widely used by that time, and in support of that they presented the pictures from the foreign journals with fractured spans, in building of which the welding was applied. Evgeny Paton, basing on the results of the first profound research works of welding process, as well as on his intuition, was firmly convinced that the cause of the disasters abroad was not in the main principles of welding process, but in its wrong primitive application. The designers used to leave the design of bridges, accepted during riveting, unchanged, i.e. they did not consider the peculiarities of the process of joining the elements using welding. Besides, the steel applied for riveting turned to be quite unsuitable for welding, and quality of welds in use of manual welding at that time was disastrously low. After Evgeny Paton had briefly stated the principles of construction of the welded bridge in Kyiv across the Dnipro river, including the selection of steel suitable for welding, the application of automatic submerged arc welding and strict control of quality of welded joints, N. S. Khrushchev (Figure 1), the Secretary of the Central Committee, resumed: «We will weld the bridge. I mean weld! Failures of other countries shall not discourage us».

In 1999, Khrushchev's four-volume book "Time, People, Power" was published a complete transcript of tape recordings made by the disgraced leader of the CPSU. In a separate essay, Khrushchev touched on the circumstances of his first meeting with Yevgeny OskarovichPaton (Khrushchev, 1999, pp. 451–453). It was around 1940:

> *"...I once received a phone call from the Ukrainian academician Paton. I had heard of him before, but had never met him. I was informed that he was a very interesting person, a major machine builder who was interested in the problem of welded bridge construction. He asked to see me, and I took him in. A dense man, already in his old age, gray-haired, stocky, with a lion's face and prickly eyes, entered the office. When he said hello, he immediately took a piece of metal out of his pocket and put it on the table: "Here, look, Comrade Khrushchev, what our institute can do. This is strip iron (10-millimeter thick, I think), and I weld it like this." I looked at the welding. Since I am a metalworker myself, I had to meet with welding. Here was just a perfect seam, outwardly smooth, like a cast. He says, "That's submerged arc welding." I heard the word "flux" for the first time then. Paton had other inventions. He told me about the possibilities of submerged-arc welding, its benefits, how it facilitates labor, increases its productivity and the quality of welded works in general, especially their reliability. He was absorbed by the idea of welding all iron structures made of ferrous metal – bridges, rafters for flooring of buildings, etc. and proved that it was more profitable to weld them instead of riveting them; he drew such a picture before me that soon he would produce automatic machines with which we would weld ships. His eyes literally burned, and his words were so confident that he made others*

believe in his idea. He was good at showing his achievements to people who were not specialists, and he was able to convince them of the correctness of his arguments. I was literally fascinated by meeting and talking with Paton, his progressive, revolutionary technical ideas. Now I can say that Evgeny Oskarovich – is the father of industrial welding in the USSR".

Figure 1. E. O. Paton and N. S. Khrushchev: a business discussion (Lobanov, 2020).

A series of studies were conducted to find suitable steel and welding materials, to work out welding modes and other important details, which were closely monitored by Glavmostostroy, the Leningrad Research Institute of Bridges, Glavstalkonstruktsiya, and the Ministry of Railways. The problem was aggravated by the fact that on January 31, 1951, the welded span of the Duplessis bridge built in 1948 collapsed in Canada (Strelko, 2023).

In 1948–1949, Voloshkevich G. Z. found during testing of technology of submerged arc welding with forced formation of vertical weld that the electrode wire is melted at arcless discharge in the fused flux, i.e. in slag pool (Lyutyi, 2015). The new type of welding appeared – electroslag welding (ESW), based on electric conductivity of the molten slag. The problems of providing the stability of electroslag process and also designing of devices for maintaining of metal and slag pools, etc. were solved.

The obtained results allowed E. O. Paton to raise the question about construction of allwelded bridge in Kyiv across the Dnipro river, applying automatic welding not only under shop conditions but also in site (Lobanov & Kyrian, 2013). The proposal of Paton, supported by the Government of the USSR, was accepted, and the technical project, and later the working projects were amended correspondingly, considering the results of the recent investigations of the PEWI and also modernized design changes in accordance with the Resolution of the Council of Ministers of the USSR of May 17, 1948 of the project assignment which related to the following points:

- truss girders of the bridge shall be welded with a solid wall of not higher than 3.6 m;
- existing type of supports shall be preserved along the whole length with girth rails on columns;
- in the navigable spans the truss girders shall be applied with the solid haunches.

In 1946–1951 Evgeny Paton, the acknowledged leader in the field of welding and bridge construction, united and organized the joint work of bridge designers and staff members of the PEWI. They carried out a large complex of research and designing works to develop further the major principles of designing of welded bridges, made by E. O. Paton as early as 1933 (Paton, 1933). As a result of this large work (Lobanov, Kyrian, & Shumitsky, 2003):

- the new design of the bridge was made. Instead of the lattice principal girders of a high height, designed before the war, four solid-wall continuous girders with chords of thin-sheet metal and economic thin wall were designed. Their height was in the limits of railway dimensions for feasibility of fabrication and transportation by large blocks. To provide a local stability of the wall, a system of horizontal stiffeners, included into composition of section of principal beams, adaptable to manufacture and welding, was used. This allowed designers to reach a record thickness of walls of principal beams 1/250, at a minimum consumption of steel which is concentrated in chords. The latter were reinforced with second sheets under supports and in the middle of spans in accordance with bending moments. Principal beams over the bridge supports were reinforced from beneath by blocks in the form of support reinforcement;

- special grade of low-carbon steel «MSt3 for welded bridges», low-sensitive to the thermodeformational cycle of welding, was developed. It was produced by control of the chemical composition (≤ 0.20 % C; 0.12-0.25 % Si; 0.36-0.60 % Mn; ≤ 0.05 % S; ≤ .045 % P) (by the way, other papers list a different grade of steel, namely M16C (Poznyakov, Dyadin, Davydov, & Dmytrienko, 2021). Silicon and aluminium were used as deoxidizers, and the set thermal condition of rolling provided a fine-grain structure. Some experimental welded spans of railway bridges were fabricated from this steel;

- improved grades of electrode wires (manganese grade A, Sv-10GA) and fluxes (AN-348, AN-348A, OSTs-45) were developed and tested under the industrial conditions;

- equipment was updated and simplified for automatic and mechanized welding of structures in shop conditions, providing stability of the preset welding condition under the industrial conditions and accuracy of electrode direction along the weld (welding tractor TS-17-M, semi-automatic machine PSh-5, holder DSh-27);

- new methods and equipment for automatic welding of vertical butt welds with their forced formation were developed for erection of spans;

- technology of shop and site welding was developed;
- design solutions of welded connections of spans and sequence of their welding were determined using criterion of assurance of preset level of strength and ductility of welded joints. These characteristics were determined from the results of testing large-sized specimens of real defect-free welded joints at minimum temperature of service (in the given case -40 °C) with a record of tension diagram. It was assumed that the satisfactory operation of welded joint under the service conditions will be guaranteed if the rupture stresses sr reach the level of ultimate strength σ_t ($\sigma_r = \sigma_t$), which is not lower than that of the parent metal. Another important requirement was the development of a high plastic deformation ($\sigma_t > \sigma_y$) before the specimen rupture;
- the metal susceptibility to strain ageing and transition to brittle state was evaluated on specific largesized specimens with a natural stress raiser in the zone of welding (narrow slot in a longitudinal composite stiffener, welded up to the plate using fillet welds).

By the beginning of the 1950s, the comprehensive experimental information on the problem of cracking in welds was collected (Lyutyi, 2015). Studied were physical-chemical properties of molten fluxes and slags at high temperatures (viscosity, electric conductivity, surface properties, thermodynamic activity of oxides). The important process is the interaction of molten slag with solidified weld metal. As a result of investigations of weldability of the low-alloy steel, carried out under the supervision of E. O. Paton, it was found that the increase in steel tendency to transition into a brittle state in the process of welding thermal cycle depends on chemical composition, method of steel deoxidation in melting and grain size. The lowcarbon steel, killed by silicon and aluminium and rolled at optimum temperature, possesses the lowest threshold of cold brittleness in the heataffected zone (Paton & Shevernytskyi, 1948a; 1948b). As to the weld metal, then to avoid the cracks it is necessary that the amount of impurities, contributing to crack formation, did not exceed the definite value and were distributed uniformly in the rolled metal section. The main result of these investigations was the working out of requirements to steels for welded structures. E. O. Paton had a meeting with I. F. Tevosyan, Ministrer of Ferrous Metallurgy, and asked him to assist in making experimental samples of steels according to the technical specifications of the Institute. The request was immediately satisfied and steel, melted in Mariupol (Ukraine), possessed a good weldability at the absence of defects. Metallurgists had to support the point of view of E. O. Paton, such as «in steel production it is necessary to take into account the requirements of welders» (and ten years later the technologies of production of metals and alloys were developed at – PEWI and implemented by metallurgists in many countries).

These and other developments served as scientific grounds for designing, fabrication and construction of the first large all-welded bridge in Europe.

"Team" – the Scientists Who Realized These Ideas.

Everyone has heard the phrase "human resources decide everything", which has become old but has not lost its sacredness. The phrase has been used by leaders of different scales, from CEOs to heads of countries, but in any case, the meaning has always remained the same: the success of any enterprise depends on the efficiency of its employees. According to some historians (Kolodiazhnyi, 2014; Strelko & Pylypchuk, 2021), the phrase belongs to Klavdiy Semenovich Nemeshaev, the head of the South-Western Railway, and later the Minister of Railways in the cabinet of Count Witte. This phrase has not lost its relevance even today.

As in many other important, large and responsible projects, "personnel decided everything" and at different stages of research, design, construction and assembly of the Kyiv Evgeny Paton Bridge.

The general design of the Evgeny Paton Bridge structure was developed by the Kyiv Special Design Bureau (SDB No. 3) of the Promstalkonstruktsiya trust (now the Limited Liability Company "V. N. Shimanovsky Ukrainian Institute of Steel Structures" (V. N. Shimanovsky Ukrinstalkon LLC) with the participation of engineers A. Shumitsky, V. Kirienko, and I. Marakin (Shymanovskyi, Kotlubei, & Shalinskyi, 2019). A group of engineers from the Institute of Electrical Welding of the Academy of Sciences of the Ukrainian SSR consisting of V. Trufyakov, V. Shevernitsky, V. Novikov, G. Zhemchuzhnikov, and S. Ostrovskaya took part in the development of the bridge project under the general supervision of E. O. Paton.

Design of the Bridge. Construction.

The shop fabrication of metal structures of bridge of a total mass of about 10,000 t was realized since December 1951 to April 1952, and the site works were made since April 1952 to October 1953 (Lobanov, Kyrian, & Shumitsky, 2003). The total length of the bridge is 1,543 m. It has 24 spans, 20 by 58 m, and four fairway arches of 87 m (Figure 2a). In transverse section the span has four principal Ibeams with a solid wall, located at 7.6 m distance from each other (Figure 2b). They are joined by transverse braces. Longitudinal braces are availableonly in the lower chord between middle principal beams along the entire length of the bridge. Over the supports the longitudinal braces were mounted between all four principal beams. Upper chords are joined by transverse rolled braces to a reinforced plate of the bridge road, operating with them for bending. The total width of the bridge is 27 m (roadway is 21 m and two pedestrian ways by 3 m). There are two tram lines in the middle of the roadway.

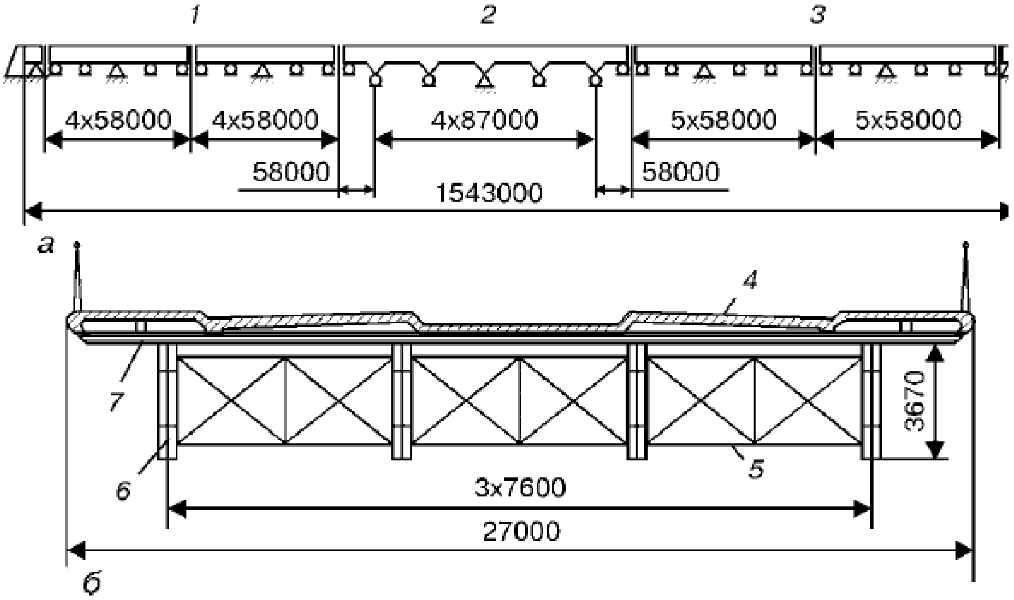


Figure 2. General scheme *(a)* and cross section *(b)* of the Evgeny Paton Bridge across the Dnipro river in Kyiv: 1 - left-bank area (two continuous four-span stiffening beams); 2 - middle area (the same, one six-span girder); 3 - right-bank area (the same, two six-span girders); 4 - reinforced-concrete plate of passageway; 5 - transverse braces between principal beams; 6 - principal welded I-beam with a solid wall; 7 - transverse rolled I-beam (Lobanov, Kyrian, & Shumitsky, 2003).

Due to earlier existing fractures of welded spans, the great attention was paid to the quality of welds, except using such design solutions of welded joints, which mostly satisfied the above-mentioned requirements for strength (Lobanov, Kyrian, & Shumitsky, 2003). Therefore, designing was based on the principle of maximum use of automatic and mechanized submerged arc welding in shop and site conditions. For this purpose, the principal beams were designed in the form of a I-beam with a solid wall having long longitudinal welds. Vertical stiffeners were replaced mainly by horizontal stiffeners. At the plant the erection elements of principal beams were manufactured in large blocks. Their length was 27–29 m and mass of about 38 t. In addition, a special design of a site butt with inserts for a vertical wall was developed that made it feasible to weld the lower chord butts by the automatic machine using run-out tabs, then their cutting and flush machining with a lower chord sheet. Butts of the vertical wall insert were designed for the automatic welding with a forced weld formation. Welding of butts with inserts of the upper chord was also provided by the automatic machines using run-out tabs, their subsequent cutting and flush machining with a chord. All this allowed 93 % of shop and 88 % of site welds of principal beams to be made by the automatic and mechanized submerged arc welding, that guaranteed their high quality.

The total length of the bridge is 1542.2 m, it consists of 24 spans (Poznyakov, Dyadin, Davydov, & Dmytrienko, 2021). The construction of the bridge began from the left bank of the Dnipro River. The right-bank part of the bridge consists of ten spans, which are overlapped by two all-welded fivespan continuous structures – (5×58) + (5×58) m. The middle part of the bridge over the navigable region of the river has six spans, which are overlapped by continuous all-welded structures – 58 + 4×87 + 58 (m). The left-bank part of the bridge has 8 spans of 58 m each and is overlapped by two four-span continuous welded structures – (4×58) + (4×58) m. In the cross-section, each structure has four main longitudinal beams of double-T section, consisting of a vertical wall with 3600 mm height and 14 mm thickness and girths of different thickness, varying from 30 to 80 mm, with a width of up to 1,000 mm (Figure 3).The stability of the beam wall is additionally provided by vertical stiffeners mounted with a step of 7.25 m. In six-span structures, the height of the wall above the intermediate supports is increased to 6,200 mm due to built on haunches.

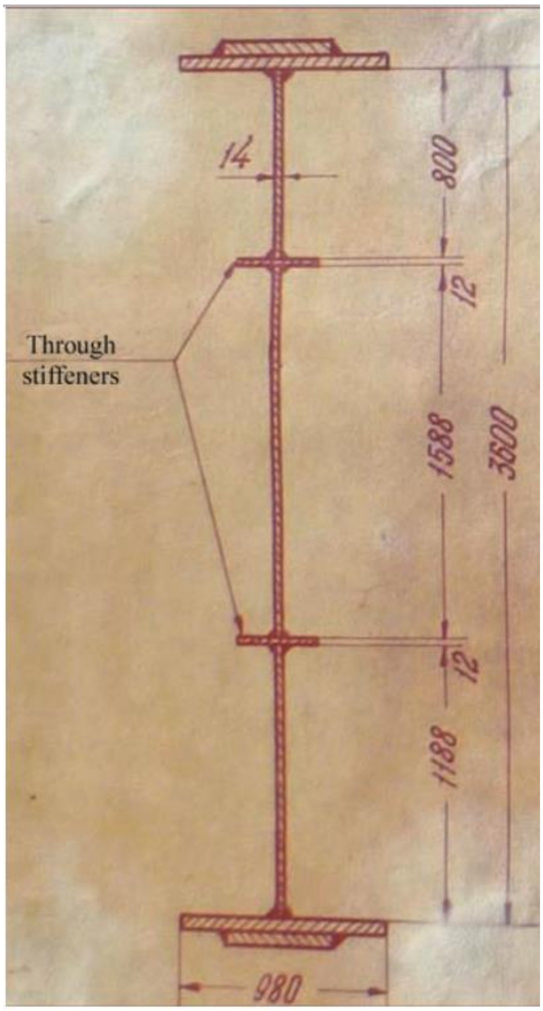


Figure 3. Cross-section of the truss of the main longitudinal beams of four- and five-span structures of the Evgeny Paton Bridge (Poznyakov, Dyadin, Davydov, & Dmytrienko, 2021).

In the process of bridge project development, a scientific school was established, as well as a methodological basis for integrated structural and technological design. As a result, the strength and durability of structures, static and fatigue resistance of welded joints, manufacturability of mechanized fabrication and welding, and large-block assembly are ensured.

So Who Named the Bridge?

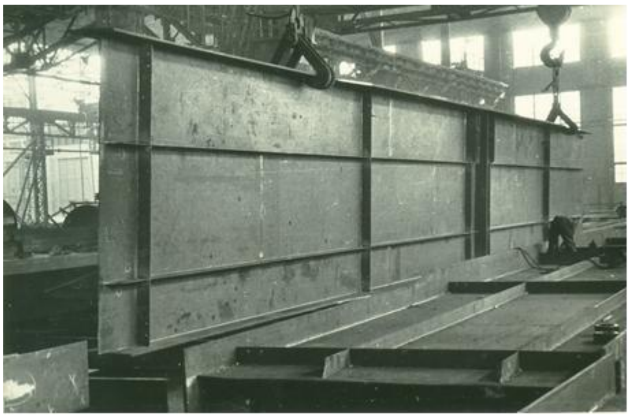
Nikita Khrushchev wrote in his memoirs. (Khrushchev, 1999, pp. 467–469): *"When Paton died, the construction of a new bridge over the Dnipro River in Kyiv was being finalized. It was the biggest bridge in Kyiv. It was all-welded. Paton pushed for it, and I supported him, that an all-welded design be adopted. He was the technical supervisor for welding the bridge. I came to Ukraine on some business at that time. The Ukrainians were running around with the idea of naming this bridge after me. It surprised me, especially because by that time we had already decided to prohibit assigning to enterprises, institutions, collective farms, etc. the names of Party and government leaders who were in good health. And even a number of honorary names, which had been assigned earlier, we withdrew by a special decision. As I jokingly said at the time, we deprived of all rights and fortunes those people who had "hoarded" factories, plants and cities. There was even an unhealthy competition whose name would be given to more enterprises or collective farms. This is a wild thing! Under Lenin, I don't think this had ever happened before. Then sometimes the name of the living Budyonny (as a hero of the Civil War) was assigned. The names of the deceased were also assigned in memory of their good deeds they had done for the Party, for the people. I asked the Ukrainians: "Why do you want to assign my name to the bridge? This is a direct violation of the decision of the Central Committee. I am against it, especially since I myself was the initiator of such a decision. Don't you realize the position you are putting me in? I ask you not to go anywhere with proposals of this nature. And why do you have to search long and hard to find out who is more worthy of having his name given to this building? Here's Academician Paton. Please, make just such a proposal, and the government will approve it". So the bridge was named after Paton. And now this bridge, as they say, is alive and well, and people passing over it, remember its creator Academician Paton with a kind word".*

Thus, with a high degree of probability, we can say that it was Nikita Khrushchev who gave the name of the Kyiv highway bridge (Evgeny Paton Bridge).

Manufacturing.

All metal structures were manufactured at the Babushkin Plant in Dnipropetrovs'k (which was then the Molotov Plant), where a special workshop was set up for the ongoing production of large blocks and assembly elements (Lobanov, 2014) (see Figures 4).


a b

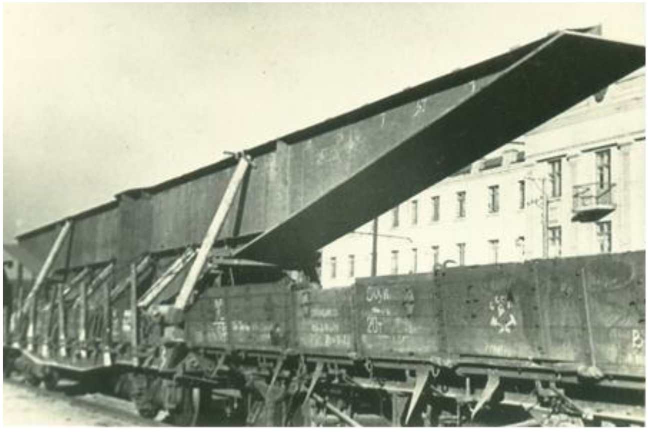



c d

Figure 4. Large-block production of metal structures for the Evgeny Paton Bridge at the plant in Dnipropetrovsk (Lobanov, 2014), where: (a) welding-on of stiffener using semi-automatic machine PSh-5 with holder DSh-27; (b) process of welding of longitudinal butts using tractor TS-17M in the tilter; (c) welding-on of edges of stiffeners; (d) Welding of girth welds of haunch in the rig (Lobanov, 2014).

The realization of construction of the bridge was entrusted to the Ministry of Municipal Economy of the USSR, which organized the Special management of bridge construction (Lobanov & Kyrian, 2013). The construction of Kyiv bridge across the Dnipro river was carried out by the staff colleagues of Kyiv department of «Proektstalkonstruktsia», plant of metal structures (Dnepropetrovsk), Bridge Construction Group No. 2 of the Ministry of Railways, the PEWI and the Ministry of Municipal Economy of the UkrSSR in close cooperation between each other.

The delivery of ready assembly elements of the bridge to Kyiv was performed by railway transport (Figures 5).


a


b

Figure 5. Transportation of metal structures of the Evgeny Paton Kyiv Bridge by rail (Lobanov, 2014), where: (a) haunch loaded on the platform; (b) echelon with main beams on the plant rails.

The workers of the Bridge Construction Group No. 2 trained and instructed by the specialists of the PEWI, carried out the welding works all the year round. The inspection, monitoring and acceptance of welding works were performed by the inspection bodies, organized and governed by the PEWI (see Figure 6 and Figure 7).

Figure 6. Construction of an all-welded bridge in Kyiv (Lobanov, 2020).

Figure 7. General view of welded site butt in the span (Lobanov & Kyrian, 2013).

The bridge was inspected by the laboratory of the Moscow Road Transport Institute both during the process of construction as well as after its completion (Lobanov & Kyrian, 2013). In conclusion the bridge was tested on static and dynamic loading (Figure 8). The tests gave the positive results.

Figure 8. Testing of the bridge (Lobanov & Kyrian, 2013).

Exploitation.

Many years of operation of welded bridges indeed confirm the reliability of their construction, provided that proper design principles, high-quality materials, and regular maintenance practices are observed. Since the mid-20th century, welded bridge structures have been widely used around the world due to their structural efficiency, reduced weight compared to riveted alternatives, and the potential for more continuous load paths. Over the decades, numerous welded bridges have demonstrated excellent durability and performance under various environmental and operational conditions. Their successful long-term service has contributed significantly to the advancement of welding standards and structural design codes, particularly in addressing issues such as fatigue, stress concentration, and the integrity of welded joints. While early concerns about the fatigue behavior of welds, especially in the heat-affected zones, led to cautious implementation, field experience and continuous monitoring have allowed engineers to refine welding techniques and improve detailing to reduce crack initiation risks. The accumulation of data from bridge inspections and load testing over time has shown that welded constructions, when properly executed, can maintain their structural integrity for many decades without significant degradation. As a result, the extended service life of numerous welded bridges around the world stands as practical evidence of their reliability, validating welded construction as a robust and enduring solution for modern infrastructure.

The Evgeny Paton Bridge across the Dnipro River in Kyiv was designed based on the conditions that the designed traffic intensity should be 10 thou cars per day (Poznyakov, Dyadin, Davydov, & Dmytrienko, 2021). During a long-term operation of the bridge, the load on its load-carrying elements gradually increased, which is associated both with an increase in the traffic intensity per day (currently it has increased by almost 10 times – during «peak» hours – up to 85 thou per day), as well as with an increase in car weight (Shymanovskyi, Kotlubei, & Shalinskyi, 2019). As a result of laying pipes of the heat pipeline and increasing the thickness of the asphalt concrete pavement, the constant loads on the bridge also increased. Taking that into account, in 1994–1998 the transverse beams of the bridge, which are located near the expansion joints, were reinforced, and additional stiffeners were mounted on some regions of vertical walls of the main beam trusses. Until 2019, the main longitudinal beams of the bridge were inspected only visually without the use of instrumental and physical methods of testing, which did not allow obtaining more detailed information on the actual technical condition of metal structures. Thus, according to the results of inspection of the bridge, performed at the end of 2018 by the specialists of LLC «V. M. Shimanovsky Ukrainian Institute of Steel Construction», it was pointed out that on the walls of the main beams of the structure in the locations of expansion welds, the formation of a layer of corrosion products was observed. Considering and analyzing the results of investigations, V. M. Shimanovsky Ukrainian Institute of Steel Construction came to the conclusion that the Evgeny Paton Bridge is in an emergrency situation and urgently needs major repairs with a partial replacement of its structural elements. This issue was repeatedly discussed at the meetings in the Kyiv City State Administration and «Kyivavtodor», on the results of which a decision was made on the reconstruction of the bridge and a need for a more detailed inspection of its structural elements. In 2019, the works on evaluation of general technical condition of the bridge were entrusted to LLC «V. M. Shimanovsky Ukrainian Institute of Steel Construction» with the involvement of specialists of the PEWI in terms of inspection of the main longitudinal beams of the bridge.

For such age bridges as Evgeny Paton Bridge, general world practice shows the following. Welded bridges that have served for many decades can benefit from a range of improvements aimed at extending their service life, enhancing safety, and optimizing performance under modern demands. One key area is the application of advanced non-destructive testing techniques, such as ultrasonic phased array or acoustic emission monitoring, which allow for early detection of fatigue cracks or internal flaws without interrupting service. Retrofit measures, such as attaching external reinforcement plates or fiber-reinforced polymer composites, can strengthen critical joints or members that have experienced stress accumulation. In cases where fatigue is a concern, techniques like toe grinding, TIG dressing, or ultrasonic impact treatment can significantly improve the fatigue resistance of welded connections by reducing stress concentrations and residual tensile stresses. Protective coatings and corrosion-resistant materials – such as weathering steel or metallization – can be applied or upgraded to enhance durability in harsh environments. Additionally, structural health monitoring systems equipped with sensors can provide real-time data on stress, strain, and environmental conditions, enabling predictive maintenance and reducing the risk of unexpected failures. Where traffic loads have increased beyond original design parameters, load distribution systems or even partial structural replacements with modern materials (like high-performance steel) may be introduced to improve capacity. Altogether, these improvements not only preserve the functionality of aging welded bridges but also adapt them to current and future performance standards.

Conclusions.

The importance of this research also lies in its relevance to sustainability and the lifecycle analysis of infrastructure. Many of the welded bridges built in the 1950s and 60s are still in operation today, and their performance over time provides a critical data set for evaluating the long-term behavior of welded joints, corrosion protection systems, and structural details. This historical performance informs modern approaches to asset management, retrofitting, and life-extension strategies. Understanding the successes and shortcomings of early welded bridge designs allows engineers and policymakers to make more informed decisions about maintaining or replacing aging infrastructure. From a historiographical perspective, this ties into broader questions about how past technological decisions continue to influence present and future possibilities – highlighting the path-dependent nature of technological development.

Finally, studying the history of all-welded bridges also provides a lens through which to examine broader themes such as industrial modernization, state-led infrastructure development, and the cultural meanings of technological progress. Bridges have long held symbolic power as markers of national pride, engineering prowess, and human ingenuity. The decision to use welding – a cutting-edge technology at the time – was often tied to narratives of progress and modernity, especially in nations seeking to assert their technological sophistication. As such, the story of all-welded bridge construction is not just a technical narrative but a cultural and political one. It intersects with themes of postwar reconstruction, economic development, labor relations, and even Cold War competition in technological display. For historians of science and technology, this intersectionality enriches our understanding of how engineering projects reflect and shape the societies in which they are embedded.

In conclusion, researching the design and construction of all-welded bridges offers valuable insights into the co-evolution of science, technology, and society. It reveals how scientific knowledge – particularly in metallurgy, structural analysis, and material fatigue – was mobilized to solve practical problems, leading to innovations that reshaped civil infrastructure. It highlights the roles of individual expertise, institutional support, and regulatory frameworks in shaping technological change. And it demonstrates how engineering is not merely a technical endeavor, but a deeply historical and cultural one, embedded within broader narratives of progress, modernization, and global exchange. By examining the history of all-welded bridges, we not only gain a better understanding of an important chapter in structural engineering but also enrich our comprehension of how science and technology operate as dynamic, interconnected forces within human history.

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Conflicts of interest.
The author declare no conflict of interest.

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Історія суцільнозварного мосту імені Євгена Патона

Анотація. *У цій статті досліджується історія науки і техніки крізь призму проектування, виготовлення та багаторічного досвіду експлуатації мосту імені Євгена Патона в Києві, першого у світі суцільнозварного автомобільного мосту. Завершений у 1953 році та названий на честь видатного піонера зварювання академіка Євгена Патона, міст став віхою в цивільному будівництві та радянських технологічних амбіціях під час повоєнної відбудови. У дослідженні розглядаються науково-технічні основи, які дозволили перехід від клепаних до зварних конструкцій, з акцентом на досягненнях у металургії, структурному аналізі та технології зварювання. Також розглядається процес виготовлення мосту, який включав широкомасштабне застосування автоматичного дугового зварювання під флюсом та інноваційні рішення для вирішення проблем, пов'язаних з цілісністю з'єднань, опором втомі та термічними напруженнями. Спираючись на архівні матеріали, технічні публікації та історичні записи, стаття розглядає міст у ширшому політичному, інституційному та економічному контексті, аналізуючи його роль як функціонального інфраструктурного проекту та символу радянського наукового прогресу. У статті розглядається історія експлуатації мосту протягом понад семи десятиліть, з акцентом на його конструкційної стійкості, методах обслуговування та отриманих уроках, які вплинули на подальше мостобудування в СРСР та в усьому світі. У статті розглядається взаємодія між науковими експериментами та практичними інженерними рішеннями,* *демонструючи, як теоретичні дослідження активно перевірялися та перевірялися шляхом реального впровадження. Подальше використання мосту в 21 столітті забезпечує живу лабораторію для вивчення довгострокової поведінки зварних сталевих конструкцій під динамічним навантаженням та стресовими факторами навколишнього середовища. Роблячи це, стаття підкреслює незмінну актуальність історичних технологічних досягнень для сучасної інфраструктурної політики, матеріалознавства та інженерної освіти. Таким чином, міст Патона служить переконливим прикладом еволюції великомасштабних зварних конструкцій та способів, якими технологічні інновації вбудовуються в ширші історичні наративи.*

Ключові слова: *історія мостобудування; історія металевих мостів; історія зварювання; Київський міст імені Євгена Патона; інженерні рішення; проблеми утримання та реставрації*

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The movement into cinema as a stage in the cinema development

Abstract. *The development of moving images is a multi-layered abstraction of movement in visual space, based on optical, mechanical, photographic and theoretical innovations. Each stage contributed to the creation of modern cinema in its technical and conceptual forms. The main aim of this study is to identify and analyze how*

scientific and technical discoveries in the fields of optics, physiology of vision, mechanics and chemistry became the basis for the emergence of a new art form – cinema, and also to show how the interaction of science, technology, culture and society contributed to the formation of a completely new system of visual thinking and mass communication. The article analyzes the history of the emergence of moving images – from optical toys of the 19th century to modern digital cinema. The emphasis is on technical, psychophysiological and technological development, as well as on modern directions that continue the evolution. The ideal "frame–interval–frame" (blackout, break) was a breakthrough in the 19th century, but it was digital technologies that gave freedom to the narrative, mixing frames in real time, adding intellectual processing and visual effects. The subject of the study was the study of the formation of scientific, technical and cultural prerequisites that led to the emergence of cinematography as a result of the evolution of knowledge about visual perception and technologies for fixing and reproducing dynamic images. Particular attention was focused on research in the field of physiology of vision, in particular on the phenomenon of persistence of visual image, which explained the illusion of movement between individual frames. The influence of technical achievements on the development of optical devices that simulated image movement, as well as the analysis of experiments with chronography, was considered. The study paid special attention to the invention of recording and projection devices. All this was considered in the context of socio-cultural and commercial processes, such as the emergence of cinemas, fair screenings, and the formation of cinema as a public spectacle. Thus, the subject of the study is not only the technical inventions themselves, but also the deeper processes of interaction of science, technology and culture, which together led to the emergence of a new means of mass communication – cinema.
Keywords: *art; culture; visual art; photography; frame; animation*

Introduction.

The term "cinematography" comes from the Greek words κίνημα ("movement") + γράφω ("to write, depict") – that is, "writing with movement" (Benis, 2023). It is the idea of movement as the essence of cinema – a natural culmination of ancient attempts to convey the dynamics of space and time through serial images, from the camera obscura (Vaniuha, Kyreia, Lemishka, Spolska, & Patron, 2024) to the praxinoscope (Lipton, 2021e) and the first film projector (Kuwahara & Fujimoto, 2022).

The emergence of the moving image – the result of a combination of discoveries in the fields of optics, mechanics, photography and the theory of perception. From primitive devices to digital sensors – cinema has gone from individual demonstration to a global visual environment.

The appearance of movement in cinema has become an extremely important stage in the cinema development, since it turned still images into living art, capable of reproducing reality in dynamics, bringing observation closer to natural human perception. Until the invention of technologies for recording and projecting motion, visual culture was limited to photography, painting, or the sequential viewing of static images that could not convey changes in states, emotions, or actions over time. Movement allowed the image to "come to life" – figures began to move, change facial expressions, and interact with space, and this was a breakthrough not only in the technical sense, but also in the viewer's perception of the artistic image. A person looking at the screen no longer simply evaluated the image, but empathized with it, because movement activated emotional involvement, created the illusion of presence. In addition, it was the emergence of movement that opened the way to the formation of a new language of cinema – montage, close-up, angles, frame duration, rhythm, which became means of cinematic thinking. The ability to capture and recreate movement allowed authors to tell stories using visual means, not only to demonstrate an event, but also to control the viewer's attention, build tension, and reveal characters. In the technical dimension, it was the result of scientific research – from the phenakistiscope, zoetrope, and other optical toys to the invention of cinema by the Lumière brothers. The principle of combining a series of photographic frames that quickly replace each other and create the effect of continuous movement became the basis of cinema as a medium. Historically, movement in cinema became the element that distinguished it from all previous forms of fine art and laid the foundation for the emergence of a new, independent art form – cinema, which combines image, time, and space. That is why the emergence of movement was not just a technical innovation, but changed the very essence of image perception, opened a new sphere of aesthetic experience, and turned cinema into the leading means of artistic and cultural influence of the 20th century.

Scientists believe that the main impetus for the appearance of motion in cinema was a combination of scientific discoveries in the field of physiology of vision, optics and image mechanics, in particular the discovery of the phenomenon of persistence of vision (delay of visual impression) and the illusion of the phi phenomenon (Bloom, 2020; Şerban, 2021; Kontou, Mills, & Menke, 2022). Persistence of vision is the ability of the human eye to retain a visual image for a short time after it has disappeared. It is thanks to this property that, if a series of individual static images with slight differences are quickly shown, the brain perceives them as continuous movement. This phenomenon became the key to understanding how to create the illusion of dynamics using successive frames. Researchers, including physicists, anatomists and opticians of the 19th century, studied the properties of vision and experimented with optical toys – phenakistiscopes, zoetropes, praxinoscopes – that demonstrated simple animation. They proved that the brain "complements" information between individual frames and perceives movement even where it is not physically present. Thus, the scientific understanding of visual perception, the development of photography and mechanisms for synchronizing images in time became the main driver for the creation of technologies that later led to the birth of cinema.

The history of the appearance of movement in cinema has been studied by many scientists of various specialties – historians of science, art historians, film critics, physiologists of vision and engineers (Gilbert, 2020; Lipton, 2021e; Veras, 2022). The subjects of research of these scientists were both technical inventions (optical devices, photography, projection devices) and the physiological principles of motion perception, as well as cultural, social and artistic aspects of the appearance and perception of motion in visual art. Their works allow to understand the cinema development not as a random event, but as a natural result of the interdisciplinary progress of science, technology and culture (Biltereyst, Maltby, & Meers, 2019; Bieberstein & Feyersinger, 2022; Vaniuha, Markovych, Hryhoruk , Matviishyn, & Toporivska, 2023).

The relevance of studying the emergence of motion in cinema from the perspective of the history of science and technology lies in the fact that this process is a vivid example of the interdisciplinary interaction of scientific discoveries, technical innovations and socio-cultural needs, which allows to understand more deeply the mechanisms of the development of scientific and technological progress in general. The study of this phenomenon shows how abstract research in the physiology of vision, optics, mechanics, chemistry of photosensitive materials and even psychology were gradually integrated into practical solutions, which ultimately led to the creation of a new form of communication – cinema. The study of the emergence of motion in cinema also makes it possible to trace how science and technology do not exist in a vacuum, but always interact with social demands, artistic searches and economic conditions. By studying this historical process, one can better understand how ideas from one field – for example, the physiology of vision – can stimulate the creation of fundamentally new technologies in a completely different – media. In addition, this topic is important for understanding how technological revolutions are formed: not only through the discoveries of lone geniuses, but as a result of the long-term accumulation of knowledge, experiments, mistakes, and exchange of ideas between scientists, engineers, artists, and entrepreneurs. By analyzing the emergence of motion in cinema, historians of science and technology receive material for modeling the general patterns of the evolution of knowledge (Barnouw, 1981; Sadoul, 1946; Utterson, 2020), the impact of scientific ideas on everyday life, and for understanding the limits and possibilities of human perception, which still determine the directions of development of modern technologies – from virtual reality to neurocinema. In this sense, the study of the origin of motion in cinema is not only historically interesting, but also methodologically valuable for a deeper understanding of the dynamics of scientific and technical creativity.

The main aim of this study is to identify and analyze how scientific and technical discoveries in the fields of optics, physiology of vision, mechanics and chemistry became the basis for the emergence of a new art form – cinema, and also to show how the interaction of science, technology, culture and society contributed to the formation of a completely new system of visual thinking and mass communication. This study aims not only to trace the technical evolution from optical toys to the cinematograph, but also to explain how the ideas that preceded these inventions were formed, what scientific concepts formed the basis of the technologies and how these concepts were transformed into applied tools capable of influencing culture and society.

Research Methods.

The article analyzes the history of the emergence of the moving image – from optical toys to digital cinema. In addition to reviewing the technical and psychophysiological aspects, a critical understanding of the influence of old technology on modern video and film practices is provided.

The methodological principles of the study of the emergence of movement in cinema from the perspective of the history of science and technology are based on an interdisciplinary approach that combines the analysis of technical, scientific, cultural and social factors. First of all, the historical-scientific method was used, which allowed to reconstruct the development of ideas, concepts and discoveries in the fields of optics, physiology of vision, mechanics, chemistry and photography, which became the basis for the creation of technologies that reproduce movement. Also important is the technical-historical analysis (Rossell, 2004; Strelko & Pylypchuk, 2021; Sayfutdinova & Galiaskarova, 2022), which made it possible to study the designs of devices (phenakistiscope, zoetrope, praxinoscope, chronograph, kinetoscope, cinematograph), the sequence of their improvement, principles of operation, authors and contexts of creation.

The method of source analysis was used (Alforova, Marchenko, Shevchuk, Kotlyar, & Honcharuk, 2021; Ebbrecht-Hartmann, Stiassny, & Henig, 2023; Oiva, et al., 2024), which included the study of archival documents, patents, publications, notes of inventors, scientific articles and memoirs of contemporaries. This made it possible to determine which scientific knowledge was used and adapted to practical needs. No less significant is the socio-cultural analysis (Pylypchuk, O. Ya., Strelko, & Pylypchuk, 2021; Weinberg et al., 2021; Vaniuha, Kyreia, Lemishka, Spolska, & Patron, 2024), which helped to reveal how social expectations, demands for spectacle, interest in the illusion of movement, mass culture and new forms of entertainment influenced the emergence and popularity of technologies that created moving images.

The method of intellectual history allowed to investigate how scientific ideas about vision, time, space and perception were formed, what philosophical and epistemological ideas underpinned technological solutions (Goodwin, 1978; Haenni, 2014; Pylypchuk, O. Ya., Strelko, Korobchenko, & Pylypchuk, O. O., 2022). In addition, the comparative method was used – to compare different versions of devices, approaches to the reconstruction of movement and the explanation of the mechanisms of its perception. An important role in the study was also played by the interpretative approach, which allowed to understand technical artifacts not only as engineering objects, but also as cultural phenomena that carried new meanings and formed new ways of seeing.

Thus, the methodology of this study is based on a set of approaches that allowed to integrate data from the history of science, technology, culture and philosophy, creating a holistic picture of how the appearance of movement in cinema was the result of a complex interaction of knowledge, technology and social context.

Results and Discussion.

Optical toys such as the thaumatrope, zoetrope, praxinoscope, and phenakistiscope were key precursors to cinema, as they first demonstrated the fundamental principles of creating the illusion of motion by rapidly changing static images (Dulac & Gaudreault, 2004; Gilbert, 2020; Kontou, Mills, & Menke, 2022). These devices, invented in the first half of the 19th century, exploited the physiological phenomenon of persistence of vision – the ability of the eye to retain an image for a short time after the disappearance of a stimulus – to create the effect of continuous motion by rapidly rotating or scrolling images. They served not only as entertaining games, but also provided inventors and scientists with a practical understanding of the mechanisms of perception of moving images, laying the theoretical and technical foundation for the subsequent development of devices capable of recording, reproducing, and projecting moving images. It was thanks to these optical illusions that the need for synchronized frame movement and lighting was realized, which ultimately led to the invention of cinema and the emergence of cinema as a new form of art and mass spectacle.

The emergence of optical toys laid not only the technical foundations (change of frames, interference of vision), but also the aesthetic and narrative basis for motion in cinema. They made motion a category that transformed space and time in cinema as a sequence of illusion, and then into the syntax of the narrative. Historiographically, these devices crossed the line from optical experiment to the artistic and production arena of public screenings, preparing society for the cinematic experience.

Thaumatrope.

The thaumatrope is an early optical illusion device invented in 1825 by the English physician John Ayrton Paris, which was an important milestone on the way to the appearance of motion in cinema, demonstrating the principles of persistence of vision and the perception of continuous motion (Wade, 2004; Riede, Johannsen, Högberg, Nowell, & Lombard, 2018; Grasnick, 2021). Structurally, the thaumatrope was a small round or oval cardboard disk image with drawings or illustrations on both sides, attached to two threads at the edges; when the disk was rapidly rotated, the threads twisted, and the images on both sides merged into one in the perception of the eye for example, the image of a bird on one side and a cage on the other rotated so that the illusion of a bird in a cage was created (see Figure 1). This simple mechanism demonstrated the basic principle of the phenomenon of persistence of vision – the ability of the human eye to retain an image for a short time after the disappearance of the stimulus, which became the foundation for the further development of animation and moving images. The thaumatrope was one of the first devices to demonstrate how rapidly changing images could create the illusion of motion, stimulating scientists and inventors to seek new devices and technologies that could reproduce a sequence of frames at a rapid pace.

a)

b)

c)

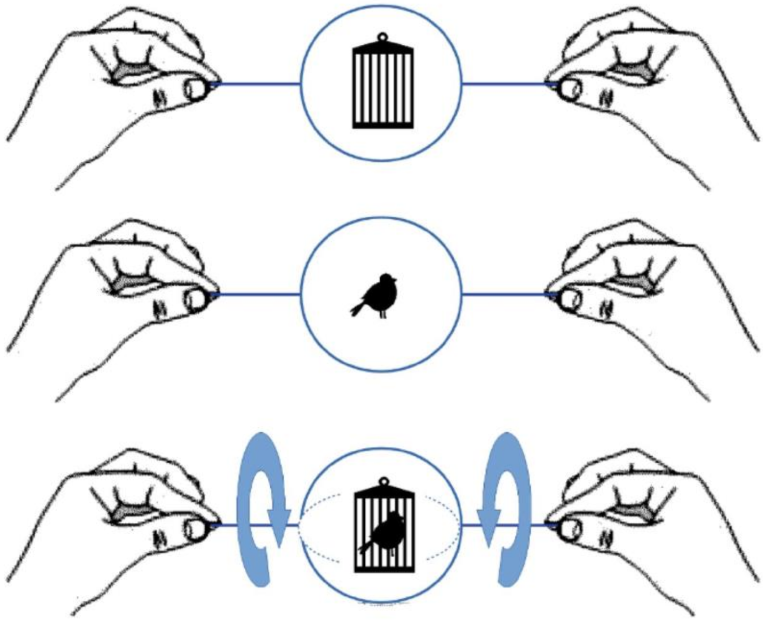

Figure 1. The holographic thaumatrope principle. Two pictures are attached to each side of the disk *(a)* and *(b)*. Attached to the disk are two pieces of string that are rapidly spun between the fingers *(c)*. (Gentet, P., Joung, Gentet, Y., & Lee, 2019).

This invention preceded such optical devices as the phenakistiscope and the zoetrope, and became the conceptual basis for later developments in cinema, where rapidly changing frames created continuous motion on the screen. Thus, the thaumatrope not only became a popular toy of the 19th century, but also played a key role in shaping the understanding of the psychological and physiological mechanisms of the perception of moving images, which ultimately led to the invention and cinema development.

Roget's Discovery.

Peter Mark Roget, a British physician, scientist, and fellow of the Royal Society of London, made important contributions to the scientific understanding of the nature of visual perception, which later played a key role in the development of the technological foundations of cinema. In 1825, he published his work "Explanation of an optical deception in the appearance of the spokes of a wheel when seen through vertical apertures" in the journal Philosophical Transactions of the Royal Society (Roget, 1825). In this work, Roget described and analyzed in detail the optical illusion that occurs when observing a moving wheel through narrow vertical apertures – for example, when the spokes of a rotating wheel appear stationary, changed, or moving in the opposite direction. This observation indicated that the human eye does not record each moment of motion separately, like a camera, but instead retains an image on the retina for a short period of time, even after the object itself has disappeared from view. This phenomenon was called the persistence of visual image, or visual after-impression (Wade, 2004; Galifret, 2006; Lipton, 2021e).

The essence of Roget's discovery was that human vision is not a continuous process of registering the real world in real time, but occurs in the form of short, successive visual impulses that our brain automatically combines into a single picture. This property of vision – a delay in perception and the ability to merge successive images – creates the conditions for the illusion of continuous motion, when individual static images shown at a certain frequency (approximately 16 frames per second or more) are perceived by us as living movement (Anderson, J. & Anderson, B., 1980). Roget was not the inventor of devices for displaying images, but his scientific analysis became the theoretical basis for the construction of optical illusions that imitated movement: the phenakistiscope, zoetrope, praxinoscope and other devices were later created taking into account this visual property described by him.

His work is considered one of the first scientific attempts to explain the physiological mechanisms of illusory movement, and it gained considerable popularity in scientific circles of the 19th century. It was thanks to it that researchers and inventors realized that to create the effect of movement, it is not necessary to make the image literally "move" – it is enough to present a series of images in the correct temporal sequence, using the ability of human vision to synthesize impressions. This is the profound methodological significance of Roget's discovery – he actually transferred research from the plane of the physical movement of an object to the study of the mechanisms of its psychophysiological perception. In addition, the research of Peter Mark Roget had an important influence on the development not only of image reproduction technologies, but also of ideas about the very nature of visual experience. He demonstrated that illusion is not an error of perception, but an important property of the visual system that allows a person to adapt to a constantly changing reality. This discovery became a kind of scientific basis for further observations by Joseph Plateau, Hermann von Helmholtz, Étienne-Jules Marey and other researchers who developed the ideas of visual persistence and worked on devices that allowed not only to study visual illusions, but to transform them into a source of aesthetic and communicative experience. Thus, Peter Mark Roget's contribution to the physiology of vision turned out to be one of the first steps towards understanding the mechanisms on which the entire cinematography would later be built – as a technical system, as an art form and as a new form of cultural expression.

Plateau's Phenakistoscope.

Joseph Antoine Ferdinand Plateau, a Belgian physicist and physiologist, became one of the most prominent researchers in the field of visual perception, and his work was fundamental to understanding the phenomenon of image persistence, a key mechanism underlying the illusion of motion and the cinema development. In 1832, Plateau published the results of his scientific experiments, in which he examined in detail why the human eye and brain perceive a sequence of static images as continuous motion if they are displayed at a sufficient speed. He found that after the visual stimulus disappears, the image does not disappear instantly, but remains on the retina for a short time – about 1/25 to 1/15 of a second (Figure 2). This delay, known as image persistence, allows the human brain to combine individual frames into a coherent picture, creating the illusion of motion (Claudet, 1865; Wade, 2016; Lipton, 2021c).

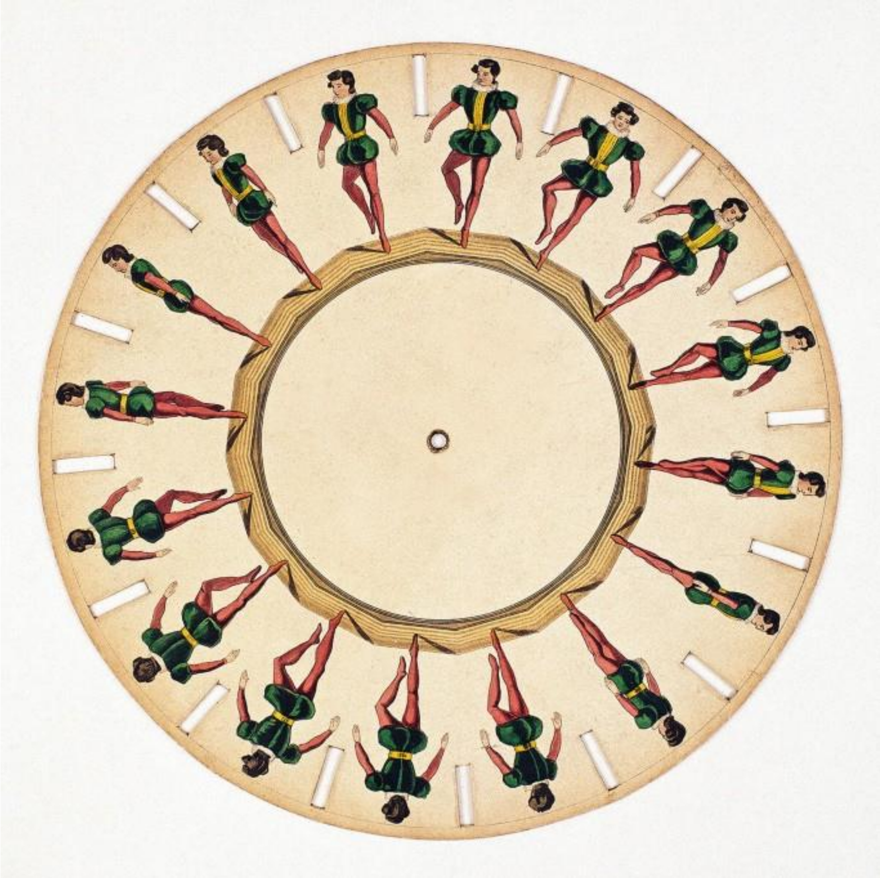

Figure 2. Phenakistoscope (Lipton, 2021c).

Plateau not only theoretically described this phenomenon, but also practically demonstrated it through the invention of an optical device – the phenakistiscope. This device consisted of a circular disk, on which a series of drawings were located around the circumference, imitating various phases of movement, as well as several slits through which the viewer could look at the rotating images. When the disk rotated at a speed corresponding to the persistence of vision, the drawings merged into a continuous moving image. The phenakistiscope became the first mechanism that made it possible to clearly demonstrate the principles that later formed the basis of animation and cinema. His invention can be considered a kind of bridge between the scientific study of visual illusions and the practical application of this knowledge to create moving images. Of particular importance in Plateau's works was the awareness of the role of the image refresh rate. He investigated how the speed of changing drawings affects the perception of movement: if the disk rotates too slowly, the illusion of movement does not arise – a person sees a sequence of separate static images; if the speed is too high, the image becomes blurry and difficult to recognize. Thus, Plateau laid the foundations for determining the optimal technical parameters that allowed achieving maximum realism of the illusion of movement – knowledge that was later used by the inventors of cinema to adjust the frame rate.

The influence of Plateau's research was extremely great and spread widely in scientific and technical circles of the 19th century. His ideas were actively adopted and developed by other scientists and inventors, such as Peter Marc Roger, Hermann von Helmholtz and Edward Muybridge (Galifret, 2006; Ayres, 2021; Lipton, 2021c). Thanks to this, the phenakistiscope and the principle of persistence of visual image became fundamental concepts that allowed the creation of the first optical toys, and later more complex devices for displaying moving images – from the zoetrope to the cinematograph.

The creation of the phenakistiscope was an important breakthrough not only from the point of view of scientific research into visual perception, but also in the context of technological development, since this device demonstrated the practical possibility of using the physiological features of human vision to create the illusion of movement. The phenakistiscope was the first invention to systematically use the principle of persistence of visual image, showing that movement can be reproduced not by actually moving an object, but by rapidly changing successive static images. This was a fundamentally new step, because previously movement in art was recorded only in static paintings, and the phenakistiscope offered the first mechanism for its reproduction in an illusory form.

The phenakistiscope was not a cinema in the modern sense, as it allowed only one viewer to view moving images at a time, through a special hole, and it also had no mechanisms for projection onto a screen. However, it was this invention that initiated a whole series of optical devices – the zoetrope, the praxinoscope, the kinetoscope, which further improved the idea of creating a moving image, and, ultimately, led to the invention of the cinema, which combined the recording, playback and mass screening of films. The phenakistiscope also made an important contribution to the development of an understanding of how to regulate the speed of image changes in order to achieve maximum realism of movement – knowledge that became the basis for determining the standard frame rate in cinema. The phenakistiscope's influence on the emergence of motion in cinema was extremely significant. It demonstrated the basic principle of cinema: movement can be created and perceived through a rapid sequence of images that the human eye and brain automatically process as continuous motion. This principle became the starting point for the development of technologies that later made it possible to capture real movement using photography and reproduce it on the screen. In addition, the phenakistiscope emphasized the importance of harmonious synchronization of the rate of frame change with the persistence time of the visual image – a parameter that became critical in the design and improvement of cinematographic devices. Knowledge of this phenomenon allowed inventors not only to create technologies that are perceived as natural movement, but also to avoid problems with flickering and blurring of the image. Thus, Joseph Plateau's phenakistiscope became not just a scientific experiment or a toy, but the first mechanism that consciously and systematically used the physiological features of vision to create a moving image. This discovery was a fundamental step on the way to the emergence of cinema – a new form of art and mass culture, which changed the way the world was perceived and the methods of transmitting information. Thanks to the phenakistiscope, the realization began that movement could be reproduced and created artificially, and not just recorded natural movements, which opened up enormous prospects for the development of visual entertainment, scientific demonstration, and later the film industry. It was Plateau's phenakistiscope that laid the theoretical and practical foundation, without which the emergence of movement in cinema as a technology and art would be impossible to imagine. In addition to its technical significance, Joseph Plateau's contribution also has a profound scientific nature, since he showed that the perception of reality is an active, complex process in which the physiological characteristics of the nervous system play an important role. His work became the foundation for further research in the field of psychology of perception, neurophysiology, and cinematic art, which to this day continue to influence the understanding of the nature of visual perception. Thanks to Joseph Plateau, we have not only a scientific explanation of how the illusion of movement arises, but also practical tools that launched a new era in the history of human culture – the era of the moving image.

Helmholtz's Works.

Hermann von Helmholtz is an outstanding German physiologist, physicist, anatomist and philosopher of science who left a deep mark on the development of the science of visual perception and played an important role in shaping the theoretical foundations of cinema. His research covered a wide range of topics related to the physiology of the eye, the mechanisms of vision and the processes of processing visual information by the brain (Hwang, 2021; Roberti & Peruzzi, 2023; Duffy, 2024). In particular, he significantly contributed to the understanding of the phenomenon that later came to be called the persistence of visual image – the ability of the visual system to retain an image on the retina for a short period of time after the disappearance of the stimulus, which became a key prerequisite for the appearance of the illusion of movement.

Helmholtz lived and worked in the second half of the 19th century – during the period of active development of physiology and experimental psychology. He combined precise laboratory research with deep theoretical analysis, which allowed him not only to confirm facts that were already known to his predecessors, such as the persistence of visual images, but also to significantly expand the understanding of these processes. He studied how the eye and brain perceive and interpret rapidly changing visual stimuli, investigated the limits and limitations of the visual system, as well as the psychological mechanisms underlying the perception of continuous motion. One of Helmholtz's significant achievements was the study of the frequency characteristics of motion perception – he investigated how the rate of change of successive images affects whether a person will see them as separate static frames or as continuous motion. His experiments showed that there is a certain optimal range of frequency of change of visual stimuli, at which images are perceived as smooth motion, as well as upper and lower limits beyond which the illusion of motion disappears. This knowledge became extremely important for the further development of cinematographic technologies, as it allowed inventors to determine the minimum number of frames per second necessary to create the effect of movement on the screen.

In addition to physiological aspects, Helmholtz also paid attention to the psychological processes associated with visual perception. He considered how the brain actively processes, completes and interprets incomplete or variable information coming from the eyes, and how this processing affects our understanding of movement and space. These ideas helped to explain why the illusion of movement occurs even when information about movement is fragmentary, and laid the foundation for research in the field of cognitive psychology and the theory of perception.

Helmholtz's works became the basis not only for the physiology of vision, but also for such sciences as psychophysics and visual research, which directly influenced the development of technologies for reproducing moving images (Hwang, 2021; Roberti & Peruzzi, 2023). His scientific discoveries provided the inventors of cinema with valuable theoretical knowledge about how best to design equipment for demonstrating motion, what frame rate and exposure parameters would ensure optimal image perception, and how to overcome the optical and physiological limitations of human vision. In general, Hermann von Helmholtz's contribution to the study of the persistence of visual images is that he systematized and deeply analyzed this phenomenon, combining physiological processes with psychological mechanisms of perception. He showed that visual experience is not simply the passive receipt of light signals, but a complex process of active image formation by the brain based on information coming from the sensory organs. His work helped the scientific and technical community to better understand how and why the human eye perceives motion from successive static frames, which ultimately became one of the fundamental principles on which the art and technology of cinematography are built. Thanks to Helmholtz's discoveries, we are able to understand the deep foundations of motion perception and the principles that allowed to transform simple images into a living, dynamic image that still captivates millions of people around the world.

Horner's Zoetrope.

The zoetrope is another of the most famous and important optical devices invented in the mid-19th century, which made a significant contribution to the development of the illusion of movement and became one of the forerunners of cinema. This device was created by the English inventor William George Horner in 1834 (Veras, 2022).

The zoetrope was a cylindrical structure, made mainly of metal or wood, with a diameter of about 20–30 cm and a height of about 15–20 cm. Vertical slots or narrow slits were evenly spaced along the sides of the cylinder, through which the viewer could look inside the device. The inner surface of the cylinder was covered with a series of sequential drawings or images that depicted different stages of the movement of an object or character – for example, a running person, a horse in motion, or a cat wagging its tail (see Figure 3.).

Figure 3. Zoetrope c.1870 (Hadjiafxendi & Plunkett, 2022).

When the zoetrope was rotated on its axis – usually by hand or with the help of a simple mechanism – the observer looked through the slits at the pictures inside. Due to the phenomenon of image persistence – that is, the delay of a visual signal on the retina, which lasts for several milliseconds after the disappearance of the stimulus – the brain processed the rapid change of successive static images as continuous movement. It was this physiological feature that made it possible to create the illusion of a living moving image from a series of still pictures that were actually drawn or printed on the inner surface of the cylinder (Kontou, Mills, & Menke, 2022).

The design of the zoetrope had several important features that affected the quality of the illusion of movement (Türkmen, 2024). First, the slits were arranged in such a way as to ensure a clear separation of the visual signals, avoiding blurring or overlapping of images. Narrow slits not only limited the field of view, but also helped to "cut off" the gaps between frames, allowing the eyes to see only one picture at a time, which significantly increased the effect of continuity of movement. Secondly, the number of pictures and slits was correlated so that at the same speed of rotation they corresponded to the same rhythm of the appearance of frames, which optimized the perception of movement. In addition, the diameter and height of the cylinder were selected for ease of viewing and an effective combination of visual and physiological parameters.

The zoetrope differed significantly from its predecessor – the phenakistiscope – in that it allowed several people to view the illusion of movement at the same time, without the need to look through the eyepiece (see Figure 4). This made the device more convenient and popular in mass use. It quickly became a popular entertainment in Victorian Europe, often demonstrated at fairs, in scientific exhibitions and even used in art installations. This fact contributed to the spread of the idea of a moving image in society and increased interest in further optical inventions.

Figure 4. Students enjoying the illusion of movement in a hand-crafted zoetrope made from a drum at Northern Vermont University's Moving Image Lab. Photo courtesy of Robby Gilbert (Gilbert, 2020).

The influence of the zoetrope on the emergence of motion in cinema was extremely significant. It demonstrated the practical implementation of the principle of sequential reproduction of static frames with a certain frequency, which allows the brain to perceive the image as continuous movement. This principle became key to the creation of subsequent optical devices – such as the praxinoscope, the kinetoscope and, ultimately, the cinematograph. The zoetrope helped inventors realize the importance of the frequency of frames and methods of demonstrating them to achieve a realistic illusion of movement. In addition, thanks to its design, it opened up the possibility of collective viewing of moving images, which became a prerequisite for the emergence of projection devices and mass film screenings (Gilbert, 2020; Kontou, Mills, & Menke, 2022; Veras, 2022).

Thus, the zoetrope became not only an important technical innovation, but also a cultural phenomenon that popularized the idea of the moving image and inspired further developments that later led to the creation of cinema – a new form of art and mass communication. Its invention revealed the potential of human vision and psyche, which allow not only to perceive, but also to actively form images of movement, which is of fundamental importance for the history of cinema and the visual arts in general.

Reynaud's Praxinoscope.

In 1877, French inventor Charles-Émile Reynaud created the praxinoscope, an innovative optical device that significantly improved and developed the ideas laid down by previous inventions, such as the phenakistiscope and the zoetrope, and became an important technological link on the way to the creation of cinema (Lipton, 2021c). The praxinoscope was designed to overcome the main shortcomings of previous devices, in particular problems with image quality and the inconvenience of viewing through narrow slits, as well as to increase the brightness and smoothness of the reproduction of moving images (Turquety, 2015).

Scholars such as Dulac & Gaudreault (2004; 2006) point out that with the advent of the praxinoscope, movement ceases to be a pure illusion – it is transformed into a narrative flow; mirrors and long turns support the principle of plot structuring and the foreshadowing of cinema. In modern media theory (Denson & Leyda, 2016) these cycles are seen as the proto-imagery "loop" of modern GIF animations, pointing to the materialism of movement and repetition as a cultural form.

The praxinoscope design consisted of a rotating cylinder, similar to a zoetrope, inside which were arranged in a circle successive drawing depicting different stages of movement (Figure 5). However, the key innovation was the installation in the center of the cylinder of a system of mirrors – usually a set of flat mirrors arranged around the axis of the cylinder so that each mirror corresponded to one drawing on the inner surface. As the cylinder rotated, the viewer looked into the central part of the device, where the mirrors reflected the internal drawings, creating a clear, unblurred and smooth image of movement. Thanks to the mirror system, it was not necessary to look through narrow slits, which significantly expanded the field of view, increased the brightness and comfort of viewing, and also reduced the flickering of the image.

The operation principle of the praxinoscope was based on the physiological phenomenon of the persistence of visual image, when the human eye retains an image on the retina for some time after the disappearance of the stimulus. The rapid rotation of the cylinder ensured a change of images with a frequency that allowed the brain to combine successive static frames into continuous movement (Cholodenko, 2024). The mirrors in the center of the praxinoscope reflected the image in such a way that each image appeared to be a separate frame, and the sequence was reproduced at the desired speed. This system made it possible to obtain a more realistic illusion of movement than was possible with the help of a phenakistiscope or a zoetrope (Eder, 1945).

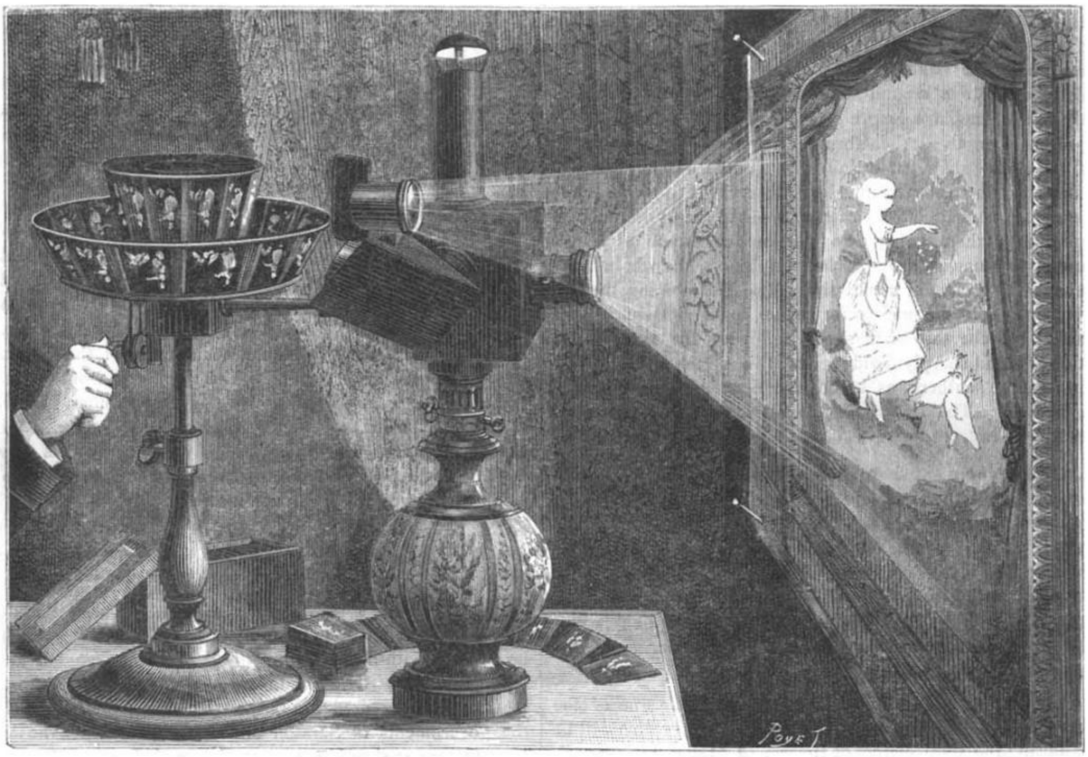

Figure 5. Émile Reynaud's praxinoscope (Tissandier, 1882, p. 357).

An important advantage of the praxinoscope was that it eliminated the main disadvantage of the zoetrope, associated with a limited field of view and obscuration of the image through narrow slits. The mirrors provided a bright and clear reflection, which made the movement smoother and more natural. This improvement greatly improved the quality of perception of moving images and made the praxinoscope popular with a wide audience. It was widely used for entertainment, educational demonstrations, and artistic experiments, becoming an important tool for the study of movement in art and science (Türkmen, 2024).

The praxinoscope influence on the emergence of movement in cinema was extremely significant and multifaceted. First of all, it became the technical basis for the development of subsequent devices, such as Thomas Edison's Kinetoscope, which combined the recording and playback of moving images. The idea of using mirrors to improve the visual effect inspired inventors to create more complex optical systems in cinema. The praxinoscope also showed that more realistic and attractive movement could be created by improving the mechanisms for displaying frames, which stimulated further technical research and experimentation (Gilbert, 2020; Lipton, 2021e; Türkmen, 2024).

In addition, the praxinoscope contributed to the popularization of the moving image as a new form of entertainment and art, increasing the public's interest in optical illusions and animation. Its convenience and efficiency made it widespread among the general public and stimulated the search for new technological solutions, which later developed into a real cinema. The praxinoscope demonstrated the importance not only of the physiological foundations of the movement perception, but also of technical factors – design and optical elements – that determine the quality of the illusion.

Thus, Emile Reynaud's praxinoscope was not just another optical toy, but a significant step forward in the development of the technique of moving images. It combined scientific knowledge about visual perception and technological innovations, opening up new horizons for the cinema development. Thanks to this device, it was confirmed that improving the methods of reproducing images can significantly improve the perception of movement and bring it closer to realistic. The praxinoscope laid the theoretical and practical foundations that later allowed 20th-century inventors to create modern cinema, which changed the cultural landscape and the way the world communicates.

"Théâtre Optique" by Émile Reynaud.

The Théâtre Optique by Émile Reynaud, invented by French engineer and inventor Émile Reynaud in 1888, was a milestone in the history of the moving image and a real technological breakthrough that greatly expanded the possibilities of demonstrating animated pictures compared to previous optical devices such as the phenakistiscope, zoetrope and praxinoscope (Dulac & Gaudreault, 2006; Kuwahara & Fujimoto, 2022; Cholodenko, 2024). It was the first device that allowed moving pictures to be projected onto a large screen, making it possible for a large audience to view them simultaneously, which significantly influenced the social and cultural significance of the moving image.

The design of the optical theater consisted of several key elements. The basis was a long tape or roll with sequential drawings – this could be a paper or cardboard medium, on which artists manually applied hundreds or even thousands of frames of animation. Each frame on the tape reflected a separate phase of movement, which together formed a continuous sequence. This tape passed through a complex mechanism that set it in motion at a constant and smooth speed in front of a light source. Light from a lamp or mirror illuminated the frames, and a system of optical lenses and mirrors projected the image onto a large screen. This optical system included sets of mirrors that provided a clear and bright display of moving pictures, minimizing distortion and shadow effects (Kuwahara & Fujimoto, 2022).

An important technical innovation of the Reynaud theater was the system for controlling the speed of the tape. Thanks to a mechanical gearbox and a pedal drive, the operator could adjust the speed of the display, which allowed for the creation of various effects of movement – from slow and smooth to fast and dynamic. This was especially important for the transmission of dramatic scenes and plot, which made the optical theater not just a technical device, but an instrument of artistic creativity. In addition, because the tape could contain long sequences of frames, the theater allowed the presentation of entire stories with a beginning, development, and conclusion, which significantly distinguished it from the short cycles of movement in the phenakistiscope or zoetrope (Lipton, 2021e).

The theater's optical system included several lenses that focused the image on the screen, providing high resolution and brightness of the projection. The mirrors were arranged in such a way as to compensate for the distortions caused by the movement of the tape and the angle of projection, which made the image clear and stable. The entire mechanism worked in close cooperation, which allowed the operator to ensure continuity of movement and avoid the flickering or blurring that was characteristic of previous devices (Dulac & Gaudreault, 2006).

One of the most famous films shown at Théâtre Optique by Émile Reynaud is *The Clown and His Dogs* (French: *Clown et ses chiens*), created in 1892. This animated film is considered one of the first in history to be shown publicly on the big screen, even before the advent of the Lumiere brothers' film projector.

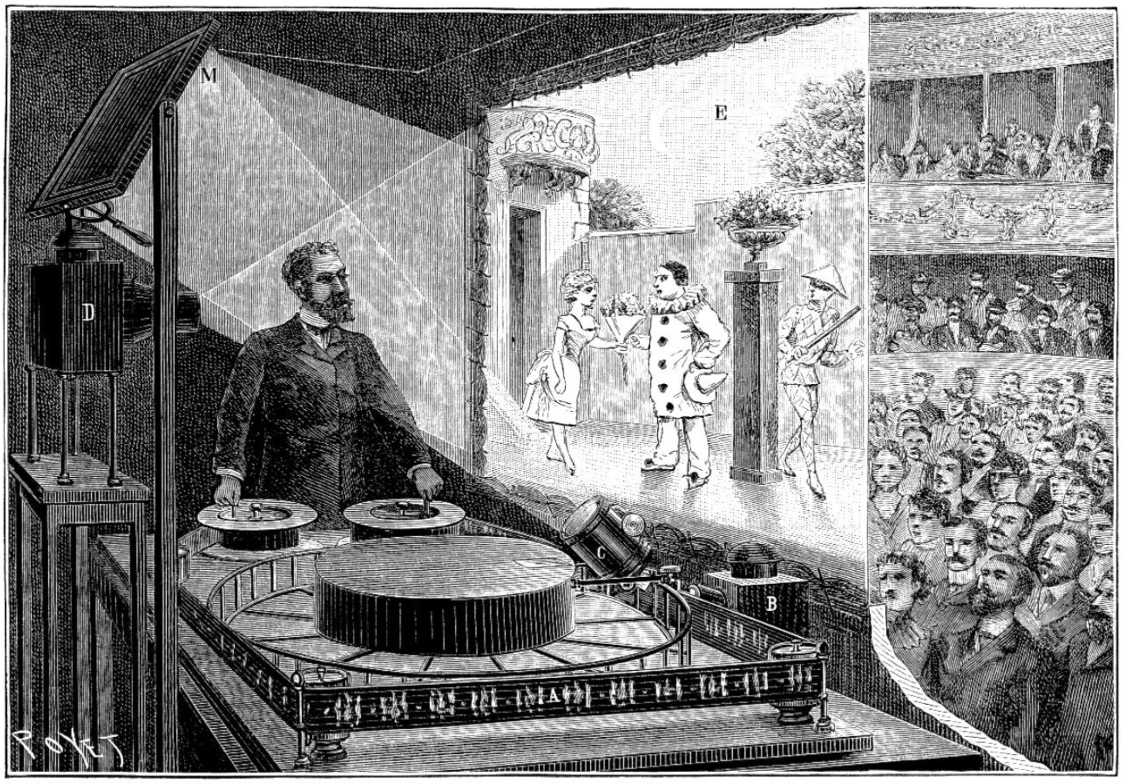

Figure 6. The Théâtre Optique by Émile Reynaud with a scene from *Pauvre Pierrot.* Gravure by Louis Poyet (Tissandier, 1892, p. 128).

The Clown and His Dog featured a dynamic scene of a clown performing tricks with his two trained dogs. The movement was rendered fluidly and vividly by the use of flexible transparent strips of hand-drawn images – approximately 500–600 frames – that were manually moved through the projection mechanism of the Théâtre Optic. This allowed for a continuous illusion of movement, and the action could be stopped and restarted at will – making the presentation more like a theatrical performance than later motion pictures.

This film, along with other Reynaud works such as *Poor Pete* (French: *Pauvre Pierrot*), demonstrated the unique style of early animation based on drawing, and was one of the first examples of how moving images could tell a story rather than merely reproduce real movement.

The influence of Émile Reynaud's optical theater on the emergence of motion in cinema was multifaceted and extremely significant (Cholodenko, 2024). First, it was the first device that allowed moving images to be shown not to a single viewer through an eyepiece, but to a large group of people simultaneously on a large screen. This created a new social format for viewing and formed the basis for mass film screenings. Second, the use of a long strip with a large number of consecutive frames was a direct technical predecessor of the film, which was later used in the cinema of the Lumière brothers and other inventors.

In addition, the optical theater demonstrated that the moving image could serve as an effective means of narration and entertainment, and not just a technical trick. This significantly influenced the cinema development as an art and business, opening the way to the formation of feature films and various genres. Reynaud not only invented the technology, but also created his own animated films, which enjoyed great success, emphasizing the importance of combining technology and creativity (Kuwahara & Fujimoto, 2022).

Thus, Émile Reynaud's optical theater was a critical stage in the development of movement in cinema, combining scientific knowledge of visual perception with technical innovations and cultural practices. This device not only confirmed the effectiveness of using sequential drawings to create the illusion of movement, but also set the standards of projection, mass viewing and narrative structure, which became the foundation for the development of 20th-century cinema. Thanks to Reynaud's theater, new opportunities were opened up for the film industry, which influenced culture and art around the world (Dulac & Gaudreault, 2006; Kuwahara & Fujimoto, 2022; Cholodenko, 2024).

Eadweard Muybridge's Experiments.

Eadweard Muybridge's experiments in motion capture, including his famous photographs of a galloping horse, were not only a sensation of their time, but also laid the foundation for the development of cinematographic technology (Lipton, 2021b). His work exemplified the combination of engineering precision, scientific curiosity, and artistic vision, and of particular value are the technical innovations he introduced in the filming process – initially with 12 cameras, and later with 24 cameras (Türkmen, 2024). Muybridge's first full-scale experiment took place on June, 1878, at the Palo Alto Racecourse, California, on the private property of Leland Stanford (Olson, 2016). The main purpose of the experiment was to prove or disprove the claim that a horse at a gallop would at some point completely lift off the ground. To record this, Muybridge placed a series of 12 large wooden cameras along the horse's path. Each camera was installed at a precise distance from each other (about 50 cm) which ensured the same time interval between exposures (Lipton, 2021b).

The most important technical achievement was the creation of an electromechanical shutter, which was activated directly by the movement of the horse (Papacosta, 2018). Along the track, he stretched thin threads that were connected to electrical contacts. When the horse ran along the track, its chest or legs cut the threads in turn, and each of the cameras was triggered sequentially (almost instantly). The shooting speed was such that each photograph captured the moment of a separate phase of the horse's body movement. The cameras used glass photographic plates that were sensitive to light, and natural sunlight was used as lighting, which required precise calculation of the shooting time.

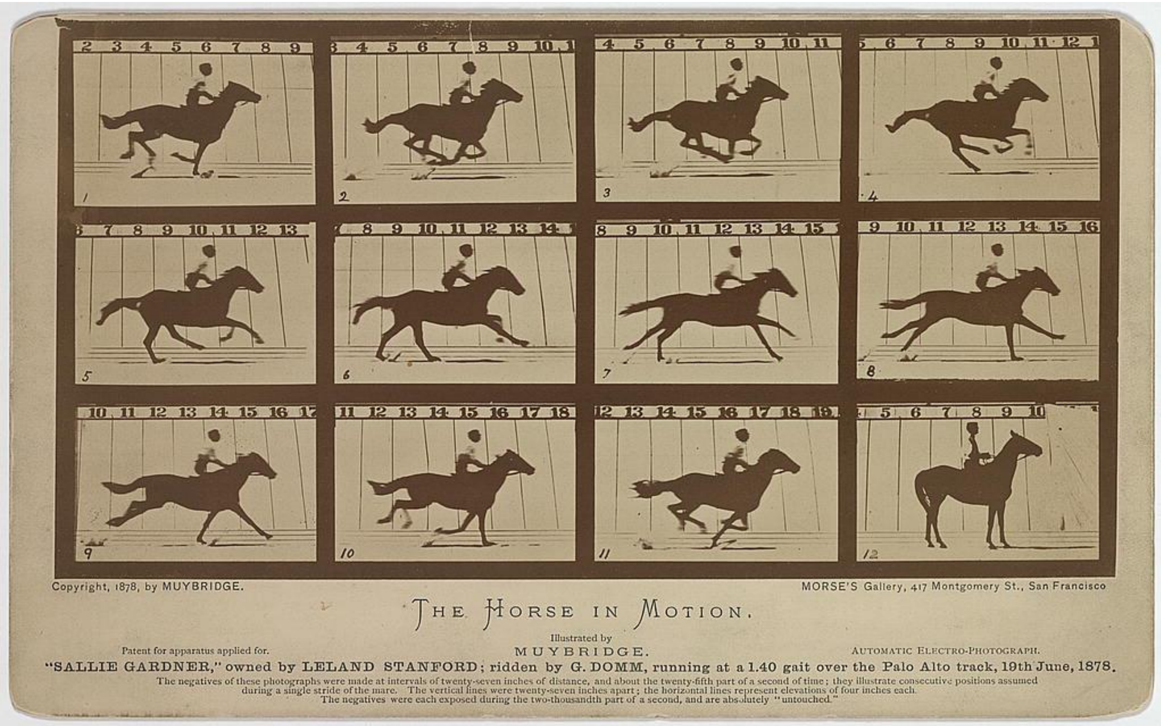

Figure 7. The Horse in motion. "Sallie Gardner," owned by Leland Stanford; running at a 1:40 gait over the Palo Alto track, 19th June/ Muybridge. California Palo Alto, ca. 1878. (Muybridge, 1878).

In 1879, Eadweard Muybridge conducted one of his most famous experiments in the study of motion, in which he first systematically used 24 cameras arranged in a row to record successive phases of dynamic human and animal movement. It was this research project, carried out in California after the successful demonstration of a galloping horse in 1878, that provided the technical, scientific, and conceptual basis for the creation of cinema, which it would become at the turn of the century (Olson, 2016). In 1879, Muybridge built a special pavilion (analogous to a modern photo studio) with a wooden platform along which 24 large-format cameras were installed in an even row at the same height. The distance between the cameras was approximately 30–40 cm, and each was directed perpendicular to the trajectory of the object. Each camera was loaded with a glass photographic plate coated with light-sensitive silver halide, designed for a short exposure.

The key innovation was the use of an electromechanical shutter mechanism, which was triggered directly by the movement of the model. Along the track, Muybridge stretched 24 cords, each of which was connected to an electrical contact that triggered the shutter of the corresponding camera. When a person or animal passed by, its body cut the cords in turn, activating each of the cameras at millisecond intervals. Thanks to this technical solution, an ideal shooting sequence was achieved, which allowed to capture the phase transitions of movement with unprecedented accuracy (Anderson, J., & Anderson, B., 1980).

The shooting was carried out outdoors in bright daylight, since the sensitivity of the emulsions of that time was very low. To compensate for this, the models (horses, dogs, people) moved along a background – a white cloth stretched behind for better contrast with the figure. Muybridge used black markings or stripes on the models' bodies and in the background to facilitate further analysis of the movement (Fresko, 2013). In some series, he began to use three rows of cameras at different angles (frontal, side and rear filming), which allowed not only to reproduce the sequence of movement, but also to study it in volume – this became the forerunner of multi-camera filming and three-dimensional cinema. He carefully processed all the negatives obtained, printed contact positives and composed them on tables that served as scientific illustrations.

The experiment of 1879 allowed Muybridge to make hundreds of unique sequences of movement. He filmed not only animals (horses, bulls, dogs, deer), but also people – men and women of different ages, including naked ones, which made it possible to study the anatomical work of muscles. Such actions as walking, running, jumping, dancing, lifting weights, throwing a discus, watering from a bucket, playing with a child, etc. were recorded.

This experiment in 1879 was the world's first systematic use of multi-camera photography for scientific purposes. It demonstrated the possibility of serializing motion – breaking it down into discrete phases and then reproducing them. All this became the basis for the concept of the moving image, which would later be embodied in film (Smiley, 2023).

Technically and conceptually, these experiments became a bridge between photography and cinema. Muybridge proved that motion could be broken down into discrete, measurable phases, which could then be reproduced again – not in real time, but with the help of a technical device. This laid the foundation for the idea of motion picture film, which in the future also consisted of successive frames. His images became the first "frames" from which the concept of the "moving image" was formed.

Thus, the meticulously planned and technically innovative experiments of Edvard Muybridge with 12 and 24 cameras became critically important not only for the scientific study of motion, but also for the birth of cinema. His research created the model of serialized imaging that underlies any film – frame by frame, movement by movement.

Zoopraxiscope.

In 1879, after a series of successful experiments in motion capture using a multi-camera setup, Edward Muybridge created a unique optical device called the Zoopraxiscope – a device that made it possible for the first time in history to demonstrate moving images to a wide audience by means of projection onto a screen (Faubel, 2015). This device was a logical continuation of his scientific research and at the same time a precursor to the movie projector. The basis of the Zoopraxiscope was a glass disk with a diameter of about 40 cm, on which a sequence of phases of one movement was applied manually or by means of photographic transfer – first in the form of silhouettes, and later in color drawings, reproduced from real photo series by Muybridge (Türkmen, 2024). The images were arranged in a circle, and the disk rotated using a manual mechanism with a friction transmission that ensured uniform movement. To create the illusion of continuous movement, a metal curtain with radial slits was placed between the light source (gas or arc lamp, later electric) and the disc – this was a stroboscopic system that allowed images to appear instantly, without overlapping one another, and activated the effect of persistence of visual image: the viewer perceived static pictures as smooth, living movement(Fresko, 2013) . The projection was carried out through a complex lens system with optical correction to focus and enlarge the image on the screen. To achieve a clear outline and high contrast, dark silhouettes on a transparent background were used, and later – colored figures drawn from the original *Animal Locomotion Series* (Figure 8–10). These discs were made by hand, often based on photonegatives, which the artists carefully converted into contour images that preserved the dynamics of each phase of the movement.

Muybridge conducted public demonstrations of the Zoopraxiscope in London, Paris, Philadelphia, New York, Chicago and other cities, accompanying the shows with comments on the physiology of movement, the theory of vision and the history of his project; the halls gathered hundreds of spectators, and the device itself began to be called a "magic window into motion" (Papacosta, 2018). This allowed him to demonstrate his series of photographs as a moving image to the public, even before the appearance of the Lumière brothers' film projectors. His lectures became the first examples in history of the synthesis of science, technology and visual art. The influence of the Zoopraxiscope on the further cinema development was decisive: technically – it was the first device to demonstrate movement through a sequence of images on a large screen, using a mechanical shutter and a projection system; conceptually – it was the first embodiment of the idea of a "moving image" as a separate phenomenon that could be reproduced, controlled and shown publicly (Faubel, 2015).

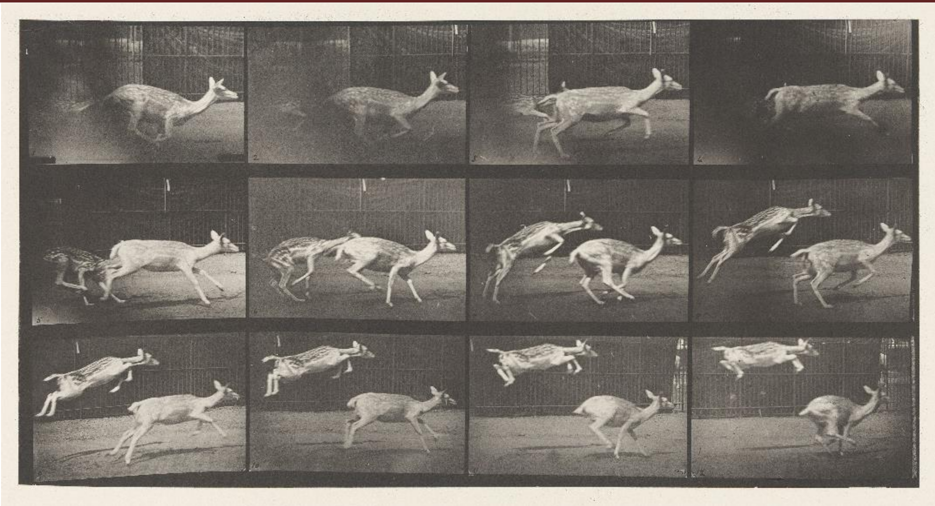

Figure 8. Two deer jumping (Muybridge, 1887a).

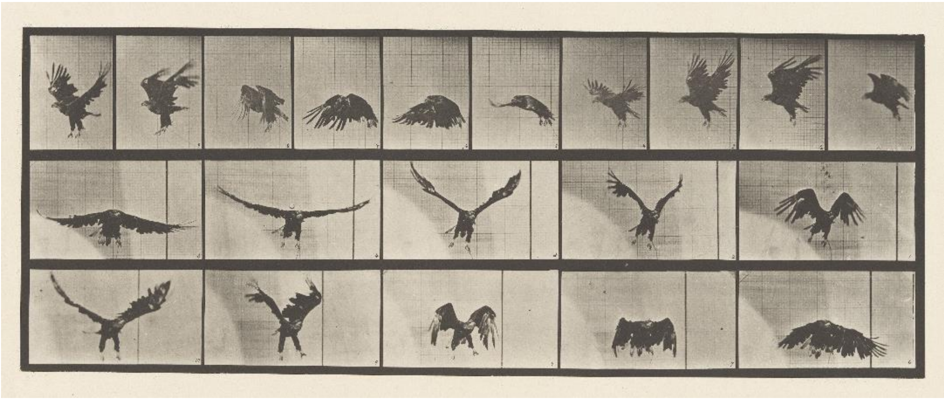

Figure 9. A bald eagle flying (Muybridge, 1887b).

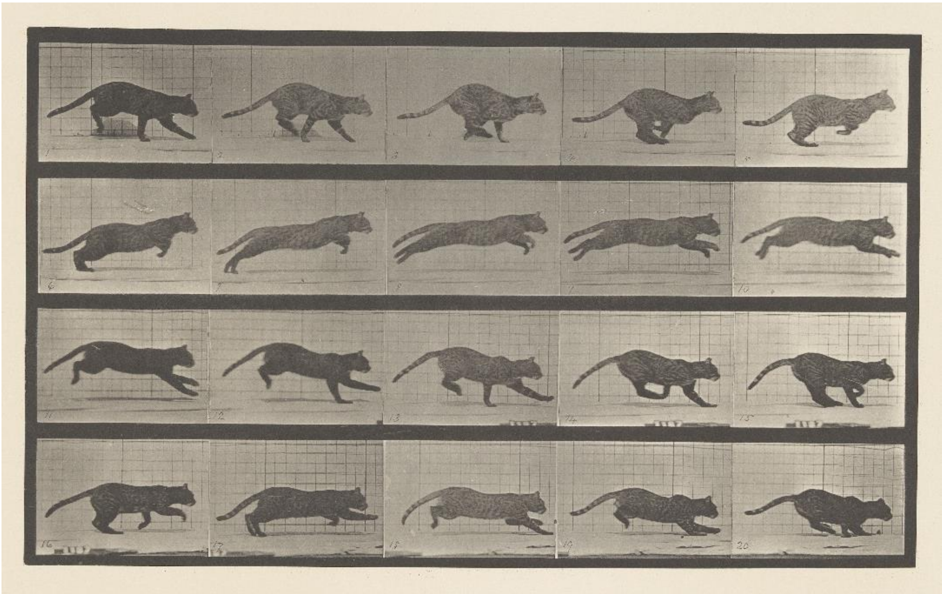

Figure 10. A bald eagle flying (Muybridge, 1887c).

The Zoopraxiscope also introduced the principle of montage – the selection and sequencing of frames to create a desired action; its principles were also directly used in the design of the film projectors of the Lumière brothers, the Skladanowsky brothers, and Edison, which replaced the glass disc with a roll of film but retained the idea of phase sequence, intermittent illumination, and optical magnification. Muybridge, by creating the Zoopraxiscope, not only showed the viewer that images could move, but he created the conditions in which scientific imagery became a source of public spectacle, and the technology of real-time reproduction became the basis for a new way of thinking about visuality and dynamics, which shaped the idea of cinema as art and technology (Schwenk & Wagner, 2010; Fresko, 2013; Lipton, 2021b).

Chronophotographic Rifle by Étienne-Jules Marey.

French physiologist, inventor, and researcher Étienne-Jules Marey made one of the most significant contributions to the development of motion capture and analysis technologies, which directly influenced the birth of cinema. His research, which began in the 1860s and 1870s and continued actively until the end of the 19th century, was focused on studying the mechanics of movement of living organisms – in particular, humans, birds, fish, horses, and other animals (Hoffmann, 2013; Lipton, 2021a; Duffy, 2024). Marey sought not only to record external forms of movement, as did Eadweard Muybridge, but also to study and accurately measure the internal physiological and kinematic processes that generate this movement. In 1882, Marey created a device that would become a landmark in the evolution of visual technology – a chronophotographic rifle (fusil chronophotographique), which allowed taking up to 12 pictures per second on a single photosensitized disk (Figure 11).

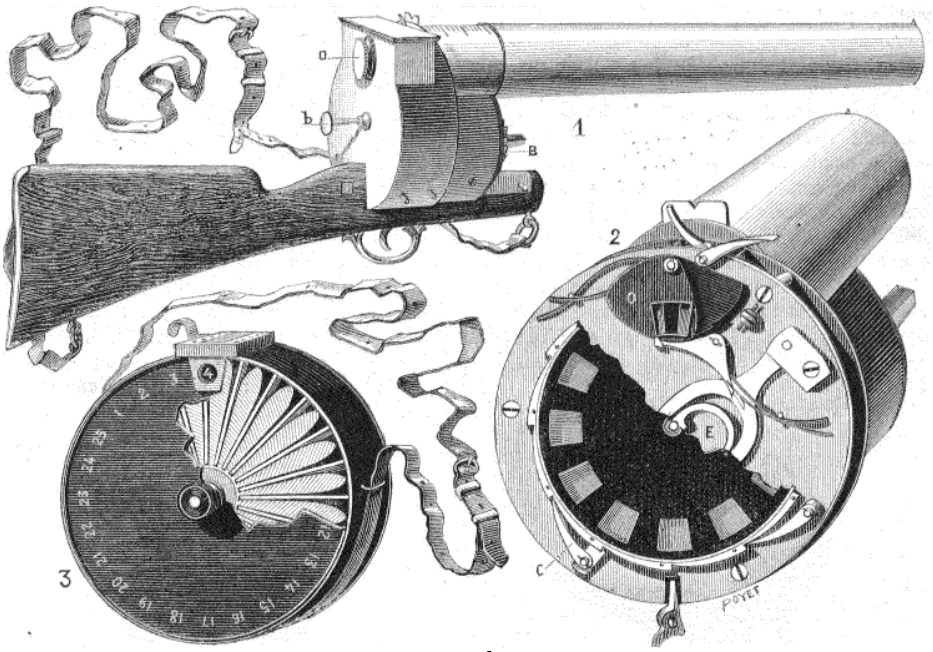

Figure 11. Chronophotographic rifle by Étienne-Jules Marey. Gravure by Louis Poyet (Marey, 1882, p. 329).

The device resembled a rifle in shape: the lens replaced the "barrel", and a round disk with a photosensitive coating – photographic film. When an object came into view, when the trigger was pressed, the disk rotated, and after short intervals of time a sequence of pictures appeared on it – one phase after another. This made it possible to record the entire cycle of movement (for example, the flight of a bird, a jump, a blow with a hand) in a single picture in the form of superimposed transparent figures located in space. Thus, Marey's chronophotography did not simply show movement – it analyzed it with mathematical precision (Duffy, 2024).

For Marey, photography was a tool of physiology. He created *the Physiological Station in Paris* (French: *La Station physiologique de Paris*) in the Parc de Monceau, where he launched complex studies with chronography, mechanography (recording movements on the smoky surface of drums), as well as pulsography, pneumography and other methods of recording bodily changes over time. His approach was deeply scientific: each image carried precise information about the position of the body in space and time, which made it possible to model, decompose and compare movements (Hoffmann, 2013).

The influence of Marey's research on the emergence of cinematography was extremely profound (Lipton, 2021a). First, his chronophotography formed the basis for subsequent inventions in the field of high-speed photography. It was the idea of a serial image on a single medium that was transformed into the concept of a film with sequentially arranged frames. Secondly, unlike Muybridge, Marey sought not simply to record movement from the outside, but to make it measurable, reproducible and analytically understandable – this formed the technical thinking that would later become characteristic of cinematographers, editors and directors. Thirdly, his ideas directly influenced Georges Demeny – one of his students, who would later invent his own projection systems, which became another step towards the emergence of cinema (Braun & Whitcombe, 1999).

Thus, Marey was not only a physiologist, but also an inventor who, at the border of science and visual technology, created a new form of vision of time. His methods made it possible to decompose dynamics into a sequence of moments, which became the foundation for the cinematic image. If Muybridge showed that movement can be seen, then Marey proved that it can be measured, controlled and reconstructed – and this is what made his chronophotography one of the cornerstones of cinema.

Kinetoscope.

The Kinetoscope was one of the first devices for viewing moving images, invented in the late 19th century, and greatly influenced the cinema development as an art and technology (Turquety, 2015; Lipton, 2021d; Türkmen, 2024). First conceptually described by American inventor Thomas Edison in 1888, it was largely developed by his collaborator William Kennedy Laurie Dixon between 1889 and 1892. Dixon and his team at Edison's laboratory in New Jersey also developed the Kinetograph, an innovative motion picture camera with rapid intermittent, or stop-motion, film movement, for shooting films for their own experiments and, later, for commercial presentations of the Kinetoscope (Turquety, 2015; Gaines, 2023).

The Kinetoscope was a device for individual viewing of short films through an eyepiece, which became an important link between the early experiments with the moving image and the mass popularization of cinema. Structurally, the kinetoscope consisted of a wooden or metal case, inside which was located the mechanism for moving the photographic film, a light source and a system of lenses for focusing the image (Figure 12). A film approximately 35 mm wide, on which frames were sequentially applied, was passed through the exposure unit – a light beam from the lamp illuminated the frames, and through a system of lenses they were projected on a miniature scale onto the eyepiece.

(a) (b)

Figure 12. Edison projecting Kinetoscope (Improved Exhibition Model), 1898. *(a)* This projecting Kinetoscope was used for traveling exhibitions; *(b)* The flyer about the projecting Kinetoscope (Peng, 2024).

An important technical feature of the kinetoscope was the film feed mechanism – an electric motor was used, which drove a toothed shaft with a system of gears and spools, which ensured smooth and precise movement of the film at a speed of about 40 frames per second. To avoid blurring of the image during frame movement, a special cam mechanism was used, which briefly stopped the film on each frame during lighting, which is the prototype of the later shutter in film projectors. This principle of synchronizing the movement of the film and lighting was extremely important for the further cinematography development (Türkmen, 2024). The kinetoscope was compact and designed for one viewer – a person looked into a small eyepiece on top of the device, which limited the mass distribution of this device, but it was this individuality of viewing that created the basis for the further development of film screenings, because it allowed for the first time to see a moving image in real time. Technically, the kinetoscope was the first system to integrate several complex engineering solutions: a mechanism for precise film feeding, frame lighting, and an optical system of lenses for focusing the image on the eye, ensuring smooth movement and high quality of the demonstration.

This device prompted engineers and inventors to look for ways to mass demonstrate moving images – this is how the first film projectors and cinemas appeared, expanding the accessibility of cinema from individual to collective viewing. Ultimately, the Kinetoscope became a critically important milestone on the path from simple optical illusions to the complex film industry, ushering in the era of cinema and laying the technological foundation for subsequent inventions that made possible the large-scale screening of motion pictures and the cinema development as such (Turquety, 2015; Peng, 2024).

Contribution of the Lumière Brothers.

The brothers Auguste and Louis Lumière, French inventors and pioneers of cinema, made a revolutionary contribution to the development of the moving image and cinema in general, creating the cinematograph – a device that combined the functions of shooting, developing and projecting films, which was a decisive step in the formation of the film industry (Galifret, 2006; Cholodenko, 2024; Türkmen, 2024). Their invention, patented in 1895, was a mechanical device capable of simultaneously recording moving frames on photographic film, developing it and projecting the image onto a screen for collective viewing, which was significantly different from previous devices, such as Edison's Kinetoscope, which was intended only for individual viewing through an eyepiece (Peng, 2024).

Technically, the Lumière cinematograph was a compact and relatively lightweight mechanism focused on precisely synchronizing the movement of the photographic film with optical illumination, which guaranteed a smooth and clear image. The film, approximately 35 mm wide, was moved by a gear mechanism that provided stepwise movement of the frames at a frequency of about 16 frames per second – a speed that optimally balanced the efficiency of motion capture and the convenience of viewing. A particularly important technical solution was the introduction of a cam mechanism system (known as a "freeze frame"), which briefly stopped the film during the exposure of a frame, preventing the moving image from blurring (Turquety, 2015). The optical part of the cinematograph included a system of lenses that allowed the projection of a large image onto a screen, providing brightness and clarity that were previously unattainable for the kinetoscope (Türkmen, 2024). The frame was illuminated by a light source (initially these were electric lamps or gas lamps), which directed a beam through the film and lenses, providing uniform and sufficient illumination for high-quality image reproduction. The Lumière brothers also developed an improved polyester film with an emulsion based on silver salts, which was distinguished by high light sensitivity and mechanical strength, which significantly improved the quality of the shooting and increased the durability of the material (Anderson, J., & Anderson, B., 1980).

Their cinematograph was portable and lightweight, which made it possible to shoot movies in various places – outdoors, in interiors, in dynamic scenes, which had previously been impossible due to the bulkiness and limitations of other devices (Turquety, 2015). The most significant technical and cultural breakthrough was the public demonstration on December 28, 1895 in Paris, which is considered the official beginning of commercial cinema; at this event, short films (in particular, *Arrival of a Train at La Ciotat Station* (French: *L'arrivée d'un train en gare de La Ciotat*)) were presented to the public, which caused a real sensation and proved the viability of the new technology for mass entertainment and cultural exchange. By integrating shooting, development, and projection in a single device, the Lumières' invention made it possible to standardize the filmmaking process, making it technologically simpler, cheaper, and more accessible, which contributed to the rapid spread of cinema in Europe and the world. The technical features of the Lumières' cinematograph – from the carefully designed gear drive mechanism and cam shutter system to improved optics and photographic film – laid the foundation for future projectors and cameras that gave impetus to the development of both feature and documentary cinema in the 20th century.

In addition, their device opened up the possibility of collective viewing, which became the basis for the emergence of cinemas and the formation of film culture (Peng, 2024). Thus, the inventions of the Lumière brothers not only ensured the technical realization of the moving image, but also laid the foundation for an entire cinematic phenomenon – from the industrial production of films to the development of cinematography, aesthetics, and film screening as mass entertainment and an art form.

Modern Technological Consequences of the Appearance of Motion in Cinema.

The appearance of motion in cinema is not just a technical progress, it is a triumph of perception, mechanics and cognition. Each step, like a puzzle of history, has made up the unique image of the moving picture that we enjoy today. The principle of "frame-interval-frame", inherent in peripheral mechanical devices, continues to exist in the decoding of event-camera data.

Modern sensors (event cameras) record the change in brightness in each pixel asynchronously, with microsecond accuracy, wide dynamic range and without motion blur – this principle is similar to the mechanical slits of old projections. Comprehensive reviews cover the characteristics and algorithms for these cameras (recognition, tracking, reconstruction) (Gallego et al., 2020). Projection mapping transforms a two-dimensional frame into a three-dimensional experience. The simultaneous projection of images onto an uneven surface creates the illusion of movement in 3D space. It is already used in cinema (e.g., the film *Oblivion*, *Audi* advertising campaigns) and VR installations.The transition to digital video was a turning point not only in the abandonment of film, but also in the rethinking of the very acts of shooting and editing – as generated data encoded in pixels.

From "*A Trip to the Moon*" by Georges Méliès's (1902) to CGI and VR – cinema has expanded its boundaries, combining practical effects and computer animation. Modernity has moved to AI, VR and MR, which leads us from frame puzzles to virtual immersion (Das, 2023). The above image processing principles find their applications in industry for recognizing fast actions and monitoring machines – for example, low-cost systems for SMEs (Walker, Turner, & Oyekan, 2024). These principles also find their application in robotics: systems (reinforcement learning) with event-cameras provide low latency and fast robot response to the environment. These technologies in combination shape the future of AR/VR, robotics, and the video analytics industry. The latest event-oriented cameras reproduce light changes in microseconds, minimizing "motion blur" – just as early mechanical frames avoided flickering through slits. Video projection mapping is based on the principle of "synchronous blinking" of images (dynamic frame streams) to create the illusion of object movement in space.

Conclusions.

This article analyzes the stages of the emergence of a moving image – from simple optical toys to the emergence of cinematographic devices and the psychophysiological justification of motion perception.

The emergence of motion in cinema is based on mechanical principles and psychophysiology. This foundation led to the development of cinematography and modern video tools. All the technologies considered are united by a common logic: "frame → interval → frame". However, it was only in the early 1890s that devices appeared that offered comprehensive solutions: shooting, storage, viewing and projection. The Zoopraxiscope taught the audience to see photographs as movement, the Kinetoscope transferred this to an individual format, and the Cinématographe made moving images accessible to mass audiences.

Modern cinema is not just the movement of pictures, but simulation, interaction and visual modeling. The basis of the moving image was born from the need to connect individual frames through mechanics and perception. It was this approach that gave rise to chronophotography and cinematography. The present – digital and "event", from the camera to the sensors – grows out of the ideas of the 19th century, but with a new dimension of reconstruction and coding of movement. Event-camera and projection mapping are logical extensions of the old idea of motion through frames and gaps. These directions are now used in robotics, VR environments, event-based cameras, and real-time projections.

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Рух у кіно, як етап розвитку кінематографу

Анотація. *Розвиток рухомих зображень – це багатошарова абстракція руху у візуальному просторі, що базувалася на оптичних, механічних, фотографічних та теоретичних новаціях. Кожен етап сприяв створенню сучасного кіно в його технічних та концептуальних формах. Основна мета даного дослідження полягає в тому, щоб виявити й проаналізувати, як наукові і технічні відкриття в галузях оптики, фізіології зору, механіки та хімії стали основою для виникнення нового виду мистецтва – кінематографу, а також показати, як взаємодія науки, технології, культури й суспільства сприяла формуванню цілком нової системи візуального мислення та масової комунікації. У статті проаналізовано історію виникнення рухомого зображення – від оптичних іграшок XIX століття до сучасного цифрового кінематографа. Акцент зроблено на технічному, психофізіологічному та технологічному розвитку, а також на сучасних напрямах, які продовжують еволюцію. Ідеальний «кадр–інтервал–кадр» (затемнення, перерва) був проривом у XIX ст., але саме цифрові технології дали свободу розповіді, змішуючи кадри в реальному часі, додаючи інтелектуальні обробки й візуальні ефекти. Предметом дослідження було вивчення формування наукових, технічних і культурних передумов, що* *зумовили виникнення кінематографа як результату еволюції знань про зорове сприйняття та технологій фіксації й відтворення динамічного зображення. Особливу увагу було зосереджено на дослідженнях у галузі фізіології зору, зокрема на явищі персистенції зорового образу, яке пояснювало ілюзію руху між окремими кадрами. Розглянуто вплив технічних досягнень на розвиток оптичних приладів, які моделювали рух зображення, а також аналіз експериментів із хронографією. У дослідженні окрему увагу приділено винайденню апаратів для запису та проєкції. Усе це розглянуто в контексті соціокультурних і комерційних процесів, таких як виникнення кінотеатрів, ярмаркових показів, формування кіно як публічного видовища. Таким чином, предметом дослідження є не лише самі технічні винаходи, а й глибші процеси взаємодії науки, техніки та культури, які спільно призвели до виникнення нового засобу масової комунікації – кінематографа.*

Ключові слова: *культура; візуальне мистецтво; фотографія; кадр; анімація*

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CONTENTS

EDITORIAL

Н а у к о в е   в и д а н н я

ІСТОРІЯ НАУКИ І ТЕХНІКИ

Том 15
Випуск 1

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