International Journal of
Mechanical and Mechatronics Engineering
ISSN: Applied | https://www.ioro.org/ijmme

# Machining: Past, Present and Future

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**Abstract**

*The study provides an in-depth analysis of the technological advancements in modern machining and its impact on the global industry. It traces the evolution from traditional subtractive manufacturing processes to emerging trends like AI-based predictive maintenance, adaptive machining, hybrid manufacturing, sustainable machining, and nanomachining for next-generation electronics and biomedical devices, including advancements in off-world manufacturing and space-ready materials. Challenges such as skill gaps in the workforce, affordability and accessibility of cutting-edge technologies, and the influence of developing nations on Industry 4.0 and 5.0 are explored. Results indicate that innovations in materials science, automation, and sustainable practices contribute significantly to precision, efficiency, and environmental sustainability in machining. The research highlights the importance of maintaining craftsmanship in the age of automation. Machining is positioned as a pivotal force and a reflection of the global shift towards a more integrated, adaptive, and sustainable industrial future.*

**Keywords:** Adaptive machining; hybrid manufacturing; sustainable practice; off-earth manufacturing; nanomanufacturing.

## 1. Introduction

Machining is a subtractive manufacturing process that shapes a workpiece into a desired geometry/shape by selectively removing material using mechanical, thermal or chemical processes. Machining processes are among the most commonly used manufacturing processes for material removal [1]. It is a manufacturing process that utilizes tools and machines to cut, drill, or shape a workpiece into the desired form [2]. This is achieved through a variety of operations including cutting, drilling, milling, turning, and grinding [1][2].

The primary purpose of machining is to remove excess material from a workpiece to achieve the desired shape and size. This is accomplished by subjecting the workpiece to a mechanical process that selectively cuts or abrades away the unwanted material [2]. Machining processes are characterized by high precision, accuracy, and surface finish, making them ideal for producing components with tight tolerances and complex geometries [3].

Machining is one of the most common manufacturing processes in the world. It can be used to create parts for a wide range of applications, including aerospace and medical devices, as well as for the automobile and construction industries [2][4]. The use of machining in engineering is extensive and can be used to create prototypes, develop products, and ensure quality control [1]. With the rapid advancement of technology, machining is also evolving to meet the needs of modern production, incorporating new materials, automation, and digital control methods [2][5].

Machining processes have been used for centuries and have a long and rich history. From the early days of hand-operated tools to the development of sophisticated mechanical processes during the Industrial Revolution [6]. Today, machining is a highly automated and digitally controlled process that is used in a wide range of industries [1] Over the years, machining has evolved and adapted to new technologies and methods, incorporating automation, new materials, and digital control systems [2][5]. The history of machining provides an insight into how machining processes have been used and adapted to meet the demands of modern manufacturing and engineering. It is a field that has seen continuous improvement and innovation, and is likely to continue evolving in the years to come.

The history of machining can be divided into three phases; the past, present and future. The past includes the early days of hand-operated tools, the Industrial Revolution, and the development of modern machining technologies [1][3]. The present includes the widespread use of CNC machines and the integration of digital control systems into machining processes [2]. The future of machining includes the use of artificial intelligence, hybrid manufacturing processes, and sustainable practices in machining [7][8]. Each phase has its own unique features and developments, and this paper will explore each phase in detail to provide a comprehensive understanding of machining and its role in engineering and manufacturing.

## 2. Methodology

The multidisciplinary research design for this paper draws on a combination of historical inquiry, human-centered analysis, and an integrative approach.

Historical inquiry provides a foundational understanding of the development and global influence of machining technologies. By analyzing historical records and advancements, from ancient hand tools to manual lathes, CNC automation, and Industry 4.0 systems, we situate current and emerging innovations within a larger technological trajectory.

Human-centered analysis, on the other hand, places emphasis on the impact of technologies on machinists, engineers, and workers, exploring dimensions such as skill development, workforce training, and accessibility, which significantly influence adoption and long-term sustainability.

The integrative approach connects the technical aspects of innovations, such as AI-driven predictive maintenance, hybrid manufacturing, sustainable machining practices, nanomachining, and off-Earth production, with economic, social, and environmental considerations. It also highlights enablers and barriers, such as cost, accessibility, and the role of developing economies in shaping the landscape of machining technologies.

Together, these methodological lenses offer a comprehensive research design that not only bridges the gap between tradition and innovation but also positions machining as a discipline that is not just technically advanced but also inclusive, adaptive, and resilient.

## 3. Machining Past: Origin and Evolution

### 3.1. Early Machining Methods: The Foundation of Precision

The history of machining began in ancient times with the use of simple hand tools like chisels, hammers, and files by craftsmen who shaped wood, stone, and metal into various forms [3]. These basic tools allowed for the manual removal of material, a process that laid the groundwork for more advanced machining techniques.

In the 13th century, early versions of lathes appeared in Europe and the Middle East. These lathes, often powered by foot pedals or bowstrings, rotated a workpiece while a cutting tool was applied by hand. This setup enabled the creation of symmetrical objects like bowls and spindles [9]. The introduction of the lathe was a significant milestone, as it introduced the concept of rotational machining.

The 18th century Industrial Revolution brought significant advancements. The introduction of milling machines, powered by hand-cranked mechanisms, allowed machinists to cut and shape metal parts with precision [10]. These machines, operated by skilled craftsmen, used rotating cutters to remove material and were crucial for producing parts for steam engines, firearms, and textile machinery [11].

### 3.2. Industrial Revolution: Rise of Steam-Powered and Mechanical Machines

A notable era was the Industrial Revolution that occurred in the late 18th century to the early 19th century [12]. The practice that once required craftsmen and their hand tools was radically transformed. Steam power took the place of human energy, where machines became the new driving force. Machines powered by steam engines were more productive and precise than humans. This pivotal period was also significant for its reconfiguration of the work structure [56].

Workshops were abandoned, and huge factories were constructed where steam engines powered the factory machines. Machines like mechanical lathes, milling machines, and drill presses were all brought into factories, setting the world on the wheels of mass production [13]. The most prominent innovations in this period were James Watt's steam engine and Henry Maudslay's screw-cutting lathe. These inventions not only set the foundation for standardization and interchangeable parts but also introduced key innovations for major industries such as textiles, transportation, and armaments [14].

The development of steam-powered machines and the like was also monumental for machinists, as they provided the opportunity to machine very high-precision metal parts. Machining evolved from an artisan trade into a science-based industrial force [15]. The establishment of engineering as a formal discipline during this time was another major shift in machining history. The field became more professional and institutionalized, and its academic dissemination paved the way for future innovation [16].

### 3.3. Electrification and Key Mile Stones in Machining

The late 19th century and early 20th century saw the introduction and popularization of electrical power for machining [17]. Machines were no longer bound by the limitations of steam or manual operation and were able to be more precise, faster, and more consistent. This was most prominently seen with the use of electric lathes and milling machines in industrial production, which could run for extended periods of time and be incorporated into assembly line production [18].

In terms of our journey's milestones, one of the most notable was the further development of the lathe. While the lathe had been mechanized by Henry Maudslay in the early 1800s, the electric lathe allowed for more precise and standardized threads as well as more complex and accurate geometries [17]. This was also the case for milling machines, which were first developed by Eli Whitney for the mass production of arms but had been further developed for more complex and precise machining of metal with rotating cutters, now using an electric motor [18].

The first steps towards automation were also being developed in this period. In the 1940s, John T. Parsons and Frank L. Stulen developed numerical control (NC) by programming a sequence of operations on a set of punched cards, which then controlled the machining operation [1]. This set the stage for the later development of computer numerical control (CNC) and the transition from manual machining to digital precision machining [19]. This period also marks the early steps of automation in machining, which would later lead to the digital revolution in manufacturing with the ability to program and execute complex operations with consistency and repeatability.

## 4. Machining Present: Modern Machining Technology

### 4.1. CNC Machining: Precision, Automation and Versatility

The Computer Numerical Control (CNC) machining is a revolutionary process that has redefined manufacturing by enabling automated and programmable control of machine tools with the help of computer software. In essence, CNC machining involves using computer programs to guide and operate machinery with high precision, allowing for the creation of complex parts and components with minimal human intervention [20][21]. One of the primary advantages of CNC machining is its ability to produce high-quality parts consistently and with minimal error, reducing material waste and increasing overall efficiency [22].

CNC machining is highly versatile, capable of working with various materials such as metals, plastics, composites, and ceramics, while executing intricate designs that would be challenging to achieve manually [20]. The process begins with the creation of a digital model using Computer-Aided Design (CAD) software, which is then used to generate tool paths through Computer-Aided Manufacturing (CAM) systems, effectively translating design into production [18]. This integration of design and manufacturing not only streamlines production but also bridges the gap between creativity and precision engineering.

The scalability of CNC machining is another significant advantage. Whether the requirement is for a single prototype or mass production of identical components, CNC machines can efficiently handle the task with consistent quality [21]. In industries like aerospace, automobile, and medical devices, where precision and reliability are critical, CNC technology ensures that parts meet the exacting tolerances and performance specifications required, making it the backbone of modern manufacturing.

Integrating sensors and real-time monitoring with CNC systems, machine operators can now anticipate maintenance needs and adjust control parameters on the fly, pushing the boundaries of smart manufacturing [23]. This convergence of hardware and software technology represents a shift towards data-driven production, where insights garnered from machine operation can further enhance productivity, reliability, and sustainability [20].

### 4.2. Advanced Material Machining: Composites, Alloys and Ceramics

The array of materials subject to modern machining has broadened well beyond conventional metals, incorporating a wide spectrum of advanced materials that offer exceptional strength, durability, and performance [24]. This progression is not only a testament to technological evolution but also mirrors the shifting demands and innovations within the industry.

Composites, such as carbon fiber-reinforced polymers, have found widespread applications in aerospace and automobile industries. Their high-strength and low-weight properties make them ideal for performance-critical components. However, the layered structure and abrasive nature of composites present challenges such as the risk of delamination and rapid tool wear. These obstacles often necessitate the use of specialized techniques such as waterjet cutting, ultrasonic machining, and high-speed milling to ensure successful machining [25]. The development and adaptation of these methods showcase the resourcefulness of machinists and engineers.

Alloys, particularly titanium and nickel-based superalloys, have become increasingly critical in a variety of industries, including aerospace and biomedical engineering. These alloys are often employed in applications that require resistance to extreme temperatures and pressures, such as jet engines and medical implants. The primary challenge in machining these alloys lie in their hardness and low thermal conductivity, which can lead to rapid tool wear and difficulty in chip evacuation [4]. To address these challenges, meticulous control of cutting parameters such as speed, feed rate, and cooling methods is often necessary.

Ceramics are recognized for their hardness and chemical stability, making them ideal for use in electronics, biomedical devices, and even as cutting tools. However, their brittleness poses significant challenges for machining, often requiring specialized techniques such as diamond-coated tools or ultrasonic-assisted machining to achieve the desired tolerances [25]. These innovations highlight the ongoing efforts of machinists to adapt to the unique properties of advanced materials.

The introduction of advanced materials into mainstream machining applications has driven significant advancements in machining technologies. This has included innovations in tool design, process optimization, and machine capabilities, underscoring the symbiosis of technological development and human ingenuity in keeping machining at the cutting edge of next-generation's engineering [24].

### 4.3. Lean Manufacturing and Industry 4.0.: Smart Factories and Driven Production

The principle of lean manufacturing merges and redefines itself with the incorporation of Industry 4.0, taking us one step closer to an intelligent machining ecosystem [26][27]. Lean manufacturing, when enhanced by Industry 4.0 technology and resources, such as IoT sensors, cloud computing, and real-time analytics, opens a new era for process optimization [28].

In the Industry 4.0-powered smart factory, machines no longer work in silos. They constantly transmit performance data, tool wear, and production metrics to centralized systems that optimize workflows in real-time [29]. Predictive maintenance becomes a norm rather than an exception with the implementation of machine learning algorithms, ensuring minimal downtime [28][30]. Virtual replicas of physical assets, better known as digital twins, let engineers simulate machining processes, test design changes, and fine-tune operations without disrupting production [27]. At the same time, adaptive control systems modulate machining parameters on the fly to ensure quality and efficiency under varying conditions [26].

This revolution goes far beyond optimization, however. It's an actionable insight-empowered productivity boost. With the efficient data analytics that have been on offer by Industry 4.0 recently, traditional workshops can be easily converted into agile, responsive manufacturing hubs. These hubs are representations of a more sustainable future for machining that lean efficiency and digital intelligence blend hand in hand [29].

## 5. Future: Innovations and Possibilities

### 5.1. Artificial Intelligence and Machine Learning: Predictive Maintenance and Adaptive Machining

The integration of artificial intelligence (AI) and machine learning (ML) heralds a new era for machining, propelling it from a reactive to a predictive and self-optimizing domain [7][31][32]. Predictive maintenance leverages AI algorithms to parse real-time sensor data streams, including vibration, temperature, and acoustic emissions, pinpointing anomalies and patterns that signal impending equipment failure.

Manufacturers can thus preemptively service machinery, curtailing unscheduled downtime and extending tool life with pinpoint accuracy [32].

Advancing further, adaptive machining utilizes ML models that vigilantly track cutting conditions, automatically recalibrating parameters such as feed rate, spindle speed, and tool trajectory on-the-fly [23]. This real-time adaptability guarantees unwavering quality even when faced with complex materials or unforeseen variations in workpiece geometry, enhancing efficiency and minimizing waste pass after pass, an embodiment of intelligence seamlessly woven into the fabric of production systems [22].

As AI becomes more deeply ingrained in CNC systems and cloud-based platforms, the future of machining will increasingly pivot towards intelligent orchestration rather than manual intervention. Machines will not only perform tasks but also anticipate, adapt, and evolve. This future will blend technological advancement with human ingenuity [8][20][27].

### 5.2. Hybrid Machining: Integrating Additive and Subtractive Processes

There is currently an increasing demand for manufacturing processes that are flexible, precise, faster, and efficient; the introduction of hybrid machining that combines additive and subtractive processes comes as an answer to these needs [33][34][35]. Additive processes like 3D printing creates parts by joining materials layer by layer to form the desired geometry. It allows printing complex geometries that would be difficult or impossible to machine traditionally, creates internal passages, lattice structures that reduces weight and has overall helped expand capabilities in designing products [35].

Subtractive processes on the other hand allows for greater precision, finish, and tolerances needed for the parts to function as intended. Techniques include CNC milling, turning, and grinding among others [36]. Integrating additive and subtractive processes into one machine allows users to create near-net shape parts using additive technology and finish them off using subtractive methods without moving the workpiece. This improves setup time, alignment between both processes, and allows unprecedented design freedom [34].

Hybrid machines are finding application in aerospace, medical, and tooling industries where components have to reach peak performance or are customized for specific tasks [35][36]. As software and hardware advance, hybrid machining is creating a future where parts aren't manufactured but intelligently engineered on demand [34].

### 5.3. Sustainable Machining: Eco-Friendly Coolant and Energy Efficient

Driving these developments is the growing consensus that sustainable machining is not a fringe area or a tick-box exercise. It is, in fact, a strategic business objective that can differentiate the cost-competitive and forward-thinking manufacturers [37]. Therefore, green principles are being integrated at every level, from materials and process design to shop-floor infrastructure. For example, traditional cutting fluids are often replaced with eco-friendly coolants such as biodegradable, water-soluble, and even plant-based formulas. These fluids are designed to minimize environmental impact while still providing excellent thermal control and machining performance [38][39]. Some systems even use dry machining or Minimal Quantity Lubrication (MQL) techniques that deliver tiny droplets of lubricant to the cutting area, reducing waste and enhancing sustainability [40].

Energy efficiency is being engineered right down to the machine's DNA. Next-generation CNC machines come with energy-saving technologies like regenerative drives, smart power management, and spindle control [41]. In addition, real-time energy monitoring systems record, analyze, and report energy consumption by each operation, providing a basis for identifying and eliminating process inefficiencies [37]. Shop floor energy is being built into an overall sustainability strategy that even optimizes supporting infrastructure like lighting and HVAC [41].

All these developments point to a brave new world of machining where business objectives and sustainability are not mutually exclusive but mutually reinforcing [38]. In this world, green machining processes and equipment play an important role by helping manufacturers combine performance and precision with safety, responsibility, and resilience.

### 5.4. Nanomachining and Microfabrication for Electronics and Biomedical Devices

Nanomachining and microfabrication are increasingly relevant to the development of next-generation electronics and biomedical devices as miniaturization and performance requirements continue to drive technology [42][43]. These high-precision machining techniques are employed on the micro- and nano-scale, allowing for the fabrication of features such as microchannels, nanopillars, and sub-micron circuitry [43]. In the electronics industry, nanomachining enables the production of high-density semiconductor components, MEMS (Micro Electro Mechanical Systems), and advanced sensors that are critical to the function of everything from smartphones to autonomous vehicles [44].

Microfabrication techniques are also enabling breakthroughs in the biomedical industry, particularly in the fields of diagnostics and treatment. These techniques make it possible to create lab-on-a-chip platforms, implantable microdevices, and drug delivery systems with a level of control and biocompatibility that was previously unattainable [24][42][43]. Nanomachining techniques such as focused ion beam milling, electron beam lithography, and atomic layer deposition enable manipulation of materials at the atomic level to precisely control surface properties and functionality [24][44].

The potential of nanomachining and microfabrication extends beyond just miniaturization, however. These techniques represent a new frontier of manufacturing that blurs the lines between the biological and the mechanical, and even pushes computation to the molecular scale [43]. This frontier is not only a showcase of the power of technological innovation but also of the potential of human creativity and collaboration to expand the reach of machining into areas previously thought to be the exclusive domain of nature [43].

### 5.5. Off-Earth Manufacturing and Space Grade Materials

A new era of machining is emerging [45][46]. Concepts like off-Earth manufacturing and in-space fabrication are being explored to produce components directly on other planets [45]. Direct manufacturing in space could help to minimize payload mass, launch expenses, and provide on-demand repairs and upgrades [47]. Technologies like in situ resource utilization (ISRU) could be leveraged to process materials from extraterrestrial sources, such as lunar regolith or Martian soil as feedstock for additive and subtractive manufacturing [45][47]. This could provide essential capabilities for manufacturing habitats, tools, and replacement parts using on-site resources.

At the same time, space-grade materials are being designed that can resist radiation, vacuum, thermal cycling, and micrometeoroid impacts [48]. Materials like titanium alloys, carbon composites, and ceramic matrix composites are being developed for spacecraft, satellites, and planetary rovers [48]. Machining these materials will require ultra-precise, contamination-free processes, often performed in cleanrooms or using remotely controlled robotic systems [48].

The convergence of advanced material science and autonomous manufacturing systems will likely play an important role in establishing sustainable infrastructure off-planet. In this new frontier, machining is not only a tool; it becomes a lifeline for survival, innovation, and exploration [46][47].

## 6. Challenges and Opportunities

### 6.1. Skill Gap and Workforce Training

With the rapid rate of technological advancement in the machining world, there is a growing skills gap, a veritable skills gap chasm that risks throttling progress [49]. On one hand, there are highly sophisticated CNC systems, computer-aided design (CAD) and manufacturing (CAM) solutions, Industry 4.0 software, etc. On the other hand, a workforce that may only have exposure to more conventional machining skills. Today's industrial tech also requires digital fluency, data analytics, and an understanding of automated processes [50]. Yet, too many vocational and technical training institutions fail to adequately adapt to the changing landscape of industry, while many people interested in entering the workforce lack a suitable and relevant skillset [49]. This results in a talent gap with a shortage of skilled machinists that can operate the state-of-the-art tools and equipment that modern manufacturers rely on.

Opportunities and innovations in training can form a powerful solution to this problem, reimagining the future of training the workforce in areas like machining, with hands-on and engaging experiences that utilize the most up-to-date in technology [51]. Augmented reality (AR) and virtual reality (VR) training programs are becoming more prevalent, allowing machinists to learn complex processes and procedures without making expensive (and irreparable) mistakes, for example. Online and modular training programs, as well as a move towards "micro-credentials" and other flexible upskilling options, have opened up doors for workers to progress and increase their own skillsets in an efficient manner. Partnerships between industry and academia to develop relevant curricula and up-to-date program offerings are also emerging and becoming more widespread [49][50].

It is not enough for manufacturers to simply continue to invest in the best new machines and equipment if they lack the people to run them. Closing the skills gap in machining and similar fields is as important as closing the "machine gap," and represents another opportunity to reap the full benefits of rapidly advancing technology in manufacturing. By ensuring there are sufficient highly trained and upskilled individuals available in the workforce, the industry can not only continue to innovate but also to do so in a way that is efficient and, therefore, sustainable [50]. In this way, training and skills development is the linchpin of the future of machining, supporting both human expertise and technological advancement.

### 6.2. Cost and Accessibility of Advanced Technology

Advanced machining technologies promise unparalleled precision and efficiency, yet their high cost poses a significant barrier to widespread adoption [52][55]. CNC machines, hybrid systems, and AI-driven platforms often come with a hefty price tag, encompassing not only the equipment itself but also software licenses, infrastructure upgrades, and skilled personnel [52]. This financial burden can stifle innovation and exacerbate the technological divide between global manufacturing powerhouses and developing regions [55].

Accessibility challenges are further compounded by supply chain limitations, restricted local availability of high-performance tools, and insufficient technical support [55]. However, within these hurdles lie opportunities for democratizing access to advanced machining. Open-source software initiatives, modular machine designs, and cloud-based platforms are making cutting-edge technologies more attainable, reducing entry barriers for smaller enterprises and resource-constrained regions [52]. Governments and industry organizations are increasingly offering grants, subsidies, and training programs to support digital transformation in manufacturing, ensuring that access to innovation is not confined to a privileged few [55].

By confronting cost and accessibility challenges head-on, the industry can cultivate a more inclusive and resilient global machining ecosystem. In this vision, innovation becomes a shared asset, transcending borders and scales to empower small and medium-sized enterprises (SMEs) and emerging economies alongside established manufacturing leaders [52].

### 6.3. Global Trends and the Role of Developing Economies

The global trends that are transforming the machining industry include automation, digitization, sustainability, and reshoring [53]. Automation with AI-driven predictive maintenance, digitization with additive manufacturing and smart factories, sustainable practices with energy-efficient machining and circular economy models, and reshoring with localized production capabilities are being adopted by manufacturers worldwide to stay competitive and meet evolving market demands [54].

Concurrently, developing economies are playing an increasingly vital role in this industry, with countries from Africa, Asia, and Latin America investing in technical education, industrial clusters, and scalable technologies to overcome traditional barriers and rapidly advance their machining sectors [53]. With abundant labor forces, emerging consumer markets, and rising digital connectivity, these regions offer significant opportunities for innovation and growth in machining [54].

Partnerships between global tech companies and local manufacturers are also catalyzing knowledge transfer and capacity building, with initiatives like mobile CNC labs, cloud-based training platforms, and government-supported incubators empowering a new generation of machinists and engineers [53]. As these developing economies continue to integrate into the global supply chain, they are not just catching up with established markets but are actively contributing to the future of machining with new perspectives, practices, and region-specific solutions [54].

## 7. Conclusion

From primitive hand tools to AI-driven, hyper-precise systems, machining has come a long way since the dawn of civilization [5]. Each innovation, each technological milestone on this journey, is a testament to humanity's relentless drive for efficiency, precision, and creativity. The evolution from manual lathes to CNC automation, from subtractive to hybrid manufacturing, has not just transformed the way we build things, but also expanded the horizons of what we dare to imagine [55].

The impact of machining's evolution is profound and far-reaching. It fuels the infrastructure of our cities, powers global trade, and provides the tools for scientific discovery and progress [55]. It's in the life-saving medical devices, in sustainable energy solutions, and the very digital gadgets that connect our world [5]. As emerging economies surge to global levels and accessibility to machining expands, the field is becoming more inclusive, more adaptive, and more visionary [53].

In essence, machining is not just a technical discipline, it's a mirror reflecting human ingenuity and aspiration. And as we stand on the threshold of Industry 5.0, the future of machining holds even greater promise, a future that will be even more collaborative, intelligent, and sustainable [5][53]. The journey is far from over. It continues, not just with machines, but with the minds that create and shape them.

## Acknowledgements

Not applicable

## Funding

This research received no external funding.

## Conflict of Interest

The authors declare no conflict of interest.

## Data Availability Statement

Not applicable

## AI Usage Disclosure

The authors used Microsoft Copilot version 150.0.4078.48 for language editing; all content was reviewed and verified by the authors.

## Author Contributions

Conceptualization, S. O. Onubaye.; methodology, S. O. Onubaye and I. O. Sadiq; analysis, all authors; writing—original draft, S. O. Onubaye.; writing—review and editing, all authors. All authors have read and agreed to the published version of the manuscript.

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