The Ascendancy of Artificial Intelligence in Modern Research: Methodological Transformations and Future Trajectories

Table of Contents

1. Introduction 2
   - 1.1. Defining Artificial Intelligence in the Context of Research 2
   - 1.2. Overview of AI's Transformative Potential in Research 2
2. Key AI Technologies Transforming Research Methodologies 3
   - 2.1. Machine Learning (ML) 3
   - 2.2. Natural Language Processing (NLP) 4
   - 2.3. Computer Vision (CV) 4
   - 2.4. Generative AI (GenAI) 5
   - 2.5. Emerging Technological Advancements (Pre-January 2025) 5
3. Transformations Across Academic Fields and Industries 6
   - 3.1. Medical and Biological Sciences 6
   - 3.2. Social Sciences and Humanities 8
   - 3.3. Technology and Engineering 10
   - 3.4. Finance 11
   - 3.5. Manufacturing 13
4. Comparative Analysis of Transformations 14
   - 4.1. Similarities in AI Adoption and Impact 14
   - 4.2. Differences in Application and Methodological Shifts 15
5. Benefits and Advantages of AI in Research 16
   - 5.1. Enhanced Efficiency and Acceleration of Discovery 16
   - 5.2. Improved Data Analysis, Accuracy, and Novel Insights 17
   - 5.3. Automation of Repetitive Research Tasks 18
6. Challenges, Limitations, and Ethical Considerations 18
   - 6.1. Technical and Operational Challenges 18
   - 6.2. Ethical and Societal Implications 22
7. Future Predictions and Expert Outlook (Pre-January 2025 Perspectives) 26
   - 7.1. Trusted Advisors and Institutional Perspectives 26
   - 7.2. Evolution of Human-AI Collaboration in Research 27
   - 7.3. Advancements in AI Capabilities for Scientific Discovery 28
   - 7.4. Philosophical Implications for Knowledge Advancement and Critical Thinking 29
8. Conclusion 30
   - 8.1. Synthesizing the Transformative Role of AI 30
   - 8.2. Balancing Innovation with Responsibility 30
   - 8.3. The Path Forward for AI in Research 31

Works cited 31

Abstract
Artificial Intelligence (AI) is rapidly reshaping the landscape of modern research, introducing profound transformations in methodologies across a multitude of academic disciplines and industrial sectors. This report provides a comprehensive analysis of AI's role, examining its fundamental technologies, the specific ways it is altering research practices, and the comparative impacts observed. It delves into the significant benefits AI offers, such as enhanced efficiency, accelerated discovery, and novel insights, while also critically evaluating the inherent challenges, limitations, and ethical considerations, including bias, transparency, data dependency, and societal implications. Drawing upon expert opinions and analyses available before January 2025, the report further explores future predictions regarding AI's continued evolution in research, emphasizing the critical balance between leveraging its transformative potential and ensuring responsible, ethical, and equitable development and deployment.

1. Introduction

The early 21st century has witnessed an unprecedented acceleration in technological advancement, with Artificial Intelligence (AI) emerging as a dominant force driving innovation and change across nearly every facet of human endeavor. In the realm of scientific and academic research, AI is not merely a new tool but a paradigm-shifting catalyst, fundamentally altering how knowledge is discovered, validated, and applied. Its capacity to process vast datasets, identify intricate patterns, and automate complex tasks is revolutionizing research methodologies that have remained largely unchanged for decades.

1.1. Defining Artificial Intelligence in the Context of Research

Artificial Intelligence, in its simplest terms, is a branch of computer science dedicated to creating machines capable of simulating human-like intelligence, including learning, comprehension, problem-solving, decision-making, and creativity.[1] These systems are designed to perceive their environment, reason about observations, and act to achieve specific goals, often autonomously.[3] At its core, AI relies on two key components: vast amounts of data and sophisticated algorithms. These algorithms, particularly those within the subset of machine learning (ML), enable AI systems to "learn" and adapt without explicit reprogramming, improving their performance over time through experience.[1]

In the context of scientific and academic research, AI refers to the application of these intelligent systems to augment and accelerate the research lifecycle. This includes tasks ranging from hypothesis generation and literature review to data collection, analysis, interpretation, and the dissemination of findings.[5] The advent of powerful AI models, especially since the release of OpenAI's ChatGPT in late 2022, has democratized access to advanced AI capabilities, further propelling its integration into research workflows.[1]

1.2. Overview of AI's Transformative Potential in Research

The transformative potential of AI in research is multifaceted and far-reaching. AI systems can analyze data with remarkable speed and accuracy, spotting patterns and providing scientists with the information needed for breakthroughs and discoveries, effectively upgrading the fundamentals of research.[1] This capability is not confined to a single domain; AI is making a global impact by tackling some of humanity's biggest challenges, from predicting and mitigating climate change effects to improving disease detection and treatment in healthcare.[1]

The integration of AI promises to enhance efficiency, automate laborious processes, and generate deeper insights across diverse fields.[1] For instance, in medical research, AI can assist in developing cures, analyzing tests, and even aiding in complex procedures.[1] In environmental science, AI can help develop green energy systems and minimize carbon emissions.[1] The overarching potential lies in AI's ability to make research faster, more efficient, and capable of addressing complexities previously beyond human capacity, leading to game-changing new technologies and a deeper understanding of the world.[1] As AI technology continues to advance, it is poised to unlock further solutions that drive progress and improve the quality of life worldwide.[1]

2. Key AI Technologies Transforming Research Methodologies

The transformative impact of AI on research is driven by several core technologies, each offering unique capabilities. These technologies are not mutually exclusive and are often integrated to create more powerful and versatile research tools.

2.1. Machine Learning (ML)

Machine learning (ML) is a fundamental subset of AI that empowers systems to learn from data and improve their performance over time without being explicitly programmed for each task.[4] ML algorithms identify patterns, predict trends, and can automate decision-making processes.[4] Key components of ML include data, models (mathematical representations of real-world processes), algorithms (methods to train models), and evaluation (assessing model performance).[4]

In research, ML is pivotal for:

- **Data Analysis and Interpretation:** ML tools are critical for analyzing and interpreting vast amounts of data quickly and efficiently, uncovering patterns and insights that would be impossible for humans to find manually.[4] This is particularly crucial given the explosion of data in recent years.
- **Automation:** ML enables the automation of various research tasks, from data collection and preprocessing to complex decision-making processes, thereby increasing efficiency and productivity.[4]
- **Solving Complex Problems:** ML has the potential to solve intricate problems in diverse domains like healthcare, finance, and environmental protection by identifying solutions not apparent through traditional methods.[4]
- **Prediction and Forecasting:** ML models excel at predicting future behaviors and trends based on historical data, which is invaluable for hypothesis generation and experimental design.[7]

The development of ML relies on strong mathematical foundations, programming skills, and expertise in data handling and preprocessing.[10] The field is characterized by rapid advancements, with tools continuously integrating cutting-edge technologies.[4]

2.2. Natural Language Processing (NLP)

Natural Language Processing (NLP) is a branch of AI focused on enabling computers to understand, interpret, and generate human language in a meaningful way.[7] This technology is crucial for analyzing the vast amounts of unstructured text data prevalent in research, such as academic papers, clinical notes, and social media content.[11]

Key applications of NLP in research include:

- **Information Extraction:** NLP can parse and understand context, coreferences, and relationships within text, enabling the rapid and scalable analysis of large datasets with greater accuracy and consistency than manual review.[12] This is vital for extracting structured information from unstructured sources like electronic health records (EHRs) or public health reports.[12]
- **Literature Review and Summarization:** Advanced NLP models like OpenAI's GPT-4 can summarize lengthy documents, assist in literature reviews, and generate human-like text, significantly speeding up the research synthesis process.[13]
- **Sentiment Analysis and Text Classification:** Models like Google's BERT are highly effective for sentiment analysis (determining the emotional tone of text) and text classification, which can be applied to analyze public opinion, patient feedback, or categorize research papers.[13]
- **Multilingual Data Processing:** Many NLP models can work with multilingual data, broadening the scope of research across different cultural and linguistic contexts.[11]

Platforms like Hugging Face Transformers provide access to a wide array of pre-trained NLP models, facilitating their integration into research workflows.[13]

2.3. Computer Vision (CV)

Computer Vision (CV) is a field of AI that enables machines to "see" and interpret visual information from images and videos, much like humans do.[14] It leverages ML and neural networks to analyze visual data, identify objects, understand scenes, and extract meaningful insights.[14]

CV is transforming research through applications such as:

- **Object Detection and Image Classification:** Identifying and categorizing objects within images (e.g., detecting pedestrians in traffic scenes or classifying cell types in medical images).[14]
- **Instance Segmentation:** Outlining the precise boundaries of each individual object in an image, even multiple objects of the same type (e.g., identifying individual car parts in manufacturing).[14]
- **Pose Estimation:** Determining the position and orientation of a person or object by predicting the location of key points (e.g., analyzing human movement in sports or animal behavior).[14]
- **Medical Image Analysis:** Assisting in the diagnosis of diseases by analyzing X-rays, CT scans, and MRIs to detect abnormalities, often with near-human accuracy.[14] For example, the CHIEF model uses CV to read digital slides of tumor tissues for cancer detection and prediction.[15]
- **Industrial Automation:** Enhancing quality control by inspecting products for defects invisible

to the human eye, and guiding robotic systems in manufacturing processes.[16]

The ability of CV to automate visual inspection, monitor processes, and analyze visual data contributes to cost and time efficiency, enhanced automation, and data-driven decision-making in research.[16]

2.4. Generative AI (GenAI)

Generative AI (GenAI) is a subset of AI that focuses on creating new, original content, including text, images, code, audio, and video, typically based on user prompts.[7] Large Language Models (LLMs) like GPT-4 are a prominent form of GenAI, trained on vast amounts of text data to understand and generate human-like language.[7]

GenAI is impacting research methodologies by:

- **Content Creation and Augmentation:** Assisting researchers in drafting manuscripts, generating code for data analysis, creating summaries, and even producing visual materials for presentations.[9]
- **Hypothesis Generation:** By synthesizing information from large datasets, GenAI can help researchers formulate novel hypotheses or identify new research directions.[9]
- **Data Synthesis and Augmentation:** GenAI can be used to create synthetic datasets for training other AI models, particularly in situations where real-world data is scarce or sensitive.[18] This can help improve the robustness and fairness of AI systems.
- **Accelerating Discovery:** Tools like OpenAI's "Deep Research" aim to produce high-quality syntheses and reports by rigorously searching and analyzing web content, potentially speeding up the initial phases of research.[18]

While GenAI offers significant potential, it also presents risks such as the generation of disinformation, intellectual property concerns, and the possibility of "hallucinations" (producing false or nonsensical information).[9] Responsible use requires human oversight and critical evaluation of AI-generated content.[9]

2.5. Emerging Technological Advancements (Pre-January 2025)

Beyond these core technologies, several emerging advancements were shaping the AI landscape in research leading up to early 2025.

- **Advanced Reasoning Capabilities:** AI models were demonstrating improved abilities to "think" through complex problems before responding. Google's Gemini 2.5 Pro, for instance, was noted for its novel problem-solving approach, excelling in math, science, and coding benchmarks.[19] The rise of **agentic AI**, systems of multiple AI agents coordinating to achieve complex goals, was also identified as a major trend, with benchmarks like the Abstraction and Reasoning Corpus (ARC) testing their ability to identify and transfer abstract patterns.[2] These reasoning models, such as OpenAI's o1 and Deepseek R1, began to automatically engage in chain-of-thought reasoning, reducing the need for extensive prompt engineering by researchers.[18]
- **Native Image Generation and Multimodal Integration:** A significant shift was the direct

integration of image generation capabilities into LLMs, moving away from separate specialized models.[19] OpenAI and Google embedded these features into their chat interfaces, allowing seamless generation of visuals alongside text.[19] This is part of a broader trend towards **multimodal AI**, which processes and integrates multiple data types (text, images, audio, video) simultaneously.[7] Vision Language Models (VLMs) and Multimodal Large Language Models (MLLMs) enable complex cross-modal understanding and generation, aiding in context-aware decision-making.[19] An example is TaxaBind, which combines six modalities for ecological research.[19] Multimodal AI mimics human understanding by analyzing diverse data sources to provide precise context and continuously improves through feedback.[7]

- **Transformer Evolution:** The transformer architecture remained the foundation of modern AI, with ongoing refinements enhancing its capabilities.[19] Transformer models revolutionized language processing by using self-attention mechanisms to weigh the relevance of all words in a sentence simultaneously, enabling more nuanced text interpretation and generation.[19] The evolution of models like Meta's LLaMA series continued to advance the state of the art.[19]

These advancements collectively point towards AI systems that are more versatile, context-aware, and capable of tackling increasingly complex research challenges.

3. Transformations Across Academic Fields and Industries

AI's influence is not uniform; its application and the nature of methodological transformations vary significantly across different academic disciplines and industrial sectors. This section explores specific examples and case studies (predominantly reflecting information available before January 2025) to illustrate these diverse impacts.

3.1. Medical and Biological Sciences

The medical and biological sciences have been among the earliest and most enthusiastic adopters of AI, driven by the complexity of biological systems, the vastness of medical data, and the urgent need for breakthroughs in disease understanding and treatment.

3.1.1. Diagnostics and Disease Detection

AI is revolutionizing how diseases are diagnosed and detected, often with enhanced speed and accuracy.

- **AI-Powered Medical Imaging:** Computer vision algorithms are increasingly used to analyze medical images such as X-rays, CT scans, and MRIs. These tools can identify subtle patterns indicative of disease that might be missed by the human eye, aiding in faster and more accurate diagnoses in areas like oncology and cardiology.[5] For example, AI can compare cancerous cells with healthy ones, assisting doctors in making better decisions.[14]
- **The CHIEF Model for Cancer Evaluation:** Scientists at Harvard Medical School designed CHIEF (Clinical Histopathology Imaging Evaluation Foundation), a versatile AI model akin to ChatGPT, capable of performing a wide array of diagnostic tasks across multiple cancer types by reading digital slides of tumor tissues.[15] CHIEF demonstrated nearly 94% accuracy in cancer detection

across 11 cancer types and outperformed existing AI methods in predicting tumors' molecular profiles and patient survival.[15] For instance, it achieved 96% accuracy in detecting EZH2 gene mutations in diffuse large B-cell lymphoma.[15] This model's ability to work with samples obtained through various methods and digitization techniques highlights its potential for broad clinical applicability.[15]

- **Prostate Cancer Prognosis:** A multimodal AI algorithm showed strong performance across racial subgroups in predicting prostate cancer prognosis, analyzing digitized biopsy slides to improve predictions without evidence of algorithmic bias. This study, involving over 5000 patients, suggested that AI can aid in personalized treatment recommendations while addressing concerns about racial disparities in outcomes.[20]
- **Predicting Biological Age:** AI tools have been developed that can predict biological age by analyzing a facial image, indicating potential for non-invasive health assessments.[21]

These examples illustrate AI's capacity to not only improve diagnostic accuracy but also to handle large-scale data and potentially reduce biases, leading to more equitable healthcare.

3.1.2. Drug Discovery and Development

The pharmaceutical industry faces immense challenges in terms of cost, time, and success rates for new drug development. AI is emerging as a powerful ally in overcoming these hurdles.

- **Accelerated Timelines:** AI significantly shortens the discovery phase. DSP-1181, the first AI-designed drug to enter clinical trials (a collaboration between Sumitomo Dainippon Pharma and Exscientia), had its discovery phase completed in just 12 months, compared to the typical 4-5 years.[22] Insilico Medicine identified new drug targets and generated candidate molecules in 18 months.[22] Recursion Pharmaceuticals advanced REC-1245 from target identification to IND-enabling studies in under 18 months, more than twice as fast as the industry average of 42 months.[22]
- **Improved Success Rates:** A study of 39 AI-native companies indicated a potential increase in Phase 1 clinical trial probability of success (PoS) from the traditional 40-65% to 80-90%.[22] As of December 2023, 21 AI-developed drugs had completed Phase I trials with this high success rate.[23] The number of AI-developed drug candidates entering clinical stages grew exponentially, from 3 in 2016 to 67 in 2023.[23]
- **Novel Target and Compound Discovery:** Insilico Medicine's Rentosertib, an IPF drug, had both its target and compound discovered using generative AI.[22] Generative AI, such as Nvidia's BioNeMo cloud service (launched March 2023) which includes models like AlphaFold2 and MoFlow, facilitates the crucial process of matching a drug's mechanism of action to specific indications and patient subpopulations, significantly reducing R&D time and costs.[22]
- **Drug Repurposing:** During the COVID-19 pandemic, BenevolentAI used its AI platform to identify baricitinib as a potential treatment in just three days, showcasing AI's capability in rapid drug repurposing.[22]
- **De Novo Design:** AI is driving towards *de novo* drug design, where the entire preclinical pipeline could be performed *in silico*, potentially saving billions in R&D costs and leading to safer, more

developable molecules.[23]

These advancements highlight AI's transformative power in making drug discovery faster, cheaper, and more successful.

3.1.3. Genomics and Personalized Medicine

AI is instrumental in deciphering the complexities of the human genome and tailoring medical treatments to individual patients.

- **Protein Structure Prediction:** The 2024 Nobel Prize in Chemistry recognized the development of AI models like AlphaFold for accurately predicting protein structures, a long-standing challenge in biology.[23] AlphaFold, developed by Google DeepMind, has significantly accelerated understanding of protein functions and interactions, which is crucial for designing new proteins and targeted therapies for diseases like Alzheimer's and Parkinson's.[8]
- **Addressing Ancestral Bias in Genetic Research:** Traditional genetic research has often been based on data from limited ancestral groups. Tools like **PhyloFrame**, developed at the University of Florida, use machine learning to account for ancestral diversity in genetic data.[25] By integrating large genomic databases with disease-specific datasets, PhyloFrame creates models better equipped to handle diverse genetic backgrounds. For example, it can predict differences between breast cancer subtypes and suggest optimal treatments irrespective of patient ancestry, thereby advancing precision medicine for underserved populations.[25] This work, published in March 2025, underscores the importance of diverse training data for equitable AI applications in genomics.[25]
- **Predicting Mutation Impacts:** Deep Genomics merges AI with genetics to predict how specific genetic mutations affect human health, proving invaluable for developing precision medicine and targeted therapies.[26]
- **Large-Scale Genomic Data Analysis:** AI, particularly ML, is essential for analyzing the massive datasets generated by genomic sequencing (e.g., processing 3 billion base pairs of DNA per person using supercomputers like HiPerGator).[25] This enables researchers to identify genetic markers for diseases, understand disease mechanisms, and develop personalized treatment strategies.[5] The NIH supports numerous projects leveraging ML for genomics and EHR data analysis.[27]

AI's role in genomics is paving the way for a new era of precision healthcare, where treatments are customized based on an individual's unique genetic and physiological profile.[5] However, the combination of AI and synthetic biology also raises significant biorisks and dual-use concerns, necessitating careful governance and early warning systems to prevent and mitigate potential biohazards.[28]

3.2. Social Sciences and Humanities

While perhaps less overtly data-intensive than the natural sciences, social sciences and humanities are also experiencing significant AI-driven transformations, particularly in how textual and qualitative data are analyzed and synthesized.

3.2.1. Analyzing Textual Data

NLP techniques are providing powerful new ways to extract insights from the vast amounts of text generated in social contexts, from social media to historical documents.

- **Inferring Psychological Constructs:** NLP can analyze text data from sources like social media posts, emails, and digitized books to infer psychological constructs such as personality traits, emotional states, intentions, social group membership, and psychological well-being.[11] For instance, researchers can infer out-group animosity from social media content or identify political orientation from texts.[11] This allows for studies with larger sample sizes than manual analysis, leading to more fine-grained and generalizable findings.[11]
- **Sentiment Analysis and Opinion Mining:** Models like BERT and GPT-4 excel at sentiment analysis, helping researchers understand public opinion on various issues, track mood changes in response to events, or analyze customer reviews.[11] This is crucial for market research, political science, and communication studies.
- **Exploratory Content Analysis:** NLP enables researchers to uncover patterns, themes, and insights from large text datasets without predefined hypotheses. This can involve frequency-based analyses, co-occurrence analysis, and clustering to understand narratives and discourse patterns, for example, on social media.[11]
- **Measuring Linguistic Bias and Novelty:** NLP can be used to measure the novelty of ideas by comparing text against large corpora or to detect linguistic bias by comparing word frequencies and contexts across different datasets, tasks difficult to perform manually due to scale.[11]
- **Multilingual Research:** NLP tools, including machine translation, can handle multilingual datasets, broadening the scope of behavioral science research across different cultural contexts.[11]

The primary advantage of NLP here is computational: automated analysis makes it feasible to analyze massive datasets, offering practical benefits like speed and consistency over manual methods.[11] Leading NLP models like OpenAI GPT-4, Google BERT, and frameworks like spaCy are instrumental in these applications.[13]

3.2.2. Evidence Synthesis and Systematic Reviews

Systematic reviews and evidence synthesis are cornerstones of research in many social science disciplines, as well as in medicine and public health. AI is streamlining these often laborious processes.

- **Automating Screening and Selection:** Tools like **Rayyan** (a free web-tool) and **Abstrackr** are designed to speed up the process of screening studies and selecting relevant citations for review.[29]
- **Full Review Automation:** Platforms like **DistillerSR** aim to automate all stages of systematic literature reviews, though they are often commercial products.[29]
- **Information Extraction:** Tools such as **ExaCT** are trained to find key information from scientific publications, such as descriptions of interventions, populations, and outcome measures, which is valuable for meta-analyses.[29]

- **Risk of Bias Assessment: RobotReviewer** is an ML system that can automatically determine information concerning trial conduct (PICO, study design) and assess the risk of bias in uploaded research articles.[29]
- **Role of Generative AI:** While current evidence (as of early 2025) suggests that GenAI should not be used for evidence synthesis without human oversight, it may assist humans in various tasks other than searching.[29] LLMs like ChatGPT show promise for aiding in systematic review-related tasks, but the technology is still considered to be in its infancy for such applications and requires careful human verification due to potential for erroneous output.[29]

The consensus is that while AI tools can be very useful at different stages of evidence reviews, it is crucial to understand their potential biases and weaknesses and often use them in conjunction with validated methods, always maintaining human oversight.[29] Frameworks like the CLEAR path (Concise, Logical, Explicit, Adaptive, Reflective) are being developed to enhance information literacy through effective prompt engineering for AI-generated content evaluation.[29]

3.3. Technology and Engineering

The technology and engineering sectors are both developers and avid users of AI, leveraging it to accelerate their own R&D cycles, design new products, and optimize complex systems.

3.3.1. R&D Process Optimization

AI is being embedded into the core R&D processes of technology companies to enhance innovation and efficiency.

- **AI Agents for Complex Tasks:** The evolution of AI agents – autonomous systems capable of handling tasks like scheduling, document summarization, insight generation, and even software debugging – is transforming R&D workflows.[30] Tools like **GitHub Copilot** act as AI coding assistants, boosting developer productivity [30], while **Notion AI** automates content creation and summarization.[30] These agents are becoming smarter at decision-making and adapting to real-world challenges, often working in hybrid teams alongside humans.[30]
- **Foundation Model Fine-Tuning:** Large-scale pre-trained foundation models (e.g., GPT-4, LLaMA, Claude) are being fine-tuned for specific domain challenges within technology R&D, from legal document analysis to personalized software recommendations.[30] This domain-specific adaptation allows organizations to extract maximum value from these powerful general-purpose models.[30]
- **Spatial Intelligence and 3D Understanding:** AI's ability to understand, reason about, and interact with 3D spaces is foundational for R&D in robotics, augmented reality (AR), virtual reality (VR), and autonomous vehicles.[30] Advances in techniques like Gaussian splatting are democratizing 3D model creation, revolutionizing fields like game development and simulation.[30]
- **Multimodal AI Development:** The development of sophisticated multimodal AI systems like OpenAI's GPT-4 Vision and Google's Gemini AI, which seamlessly combine text and visual data, is a key R&D focus. These systems are critical for creating more intuitive and comprehensive AI applications.[30]

- **Custom Silicon for AI Workloads:** Technology companies are increasingly investing in custom silicon (ASICs) designed for particular AI tasks, driven by the immense compute demand of AI reasoning and model training.[31] ASICs offer higher efficiency and performance for specific AI workloads compared to general-purpose GPUs, although GPUs provide greater flexibility.[31]

The focus in 2025 for technology companies is on building AI platforms that meet enterprise customer needs for optimized performance, profitability, and security, often through partnerships across the AI ecosystem.[31]

3.3.2. Materials Science

The discovery and design of new materials with specific properties is a time-consuming and expensive process. AI, particularly generative AI, is beginning to revolutionize materials science research.

- **Discovery of Novel Materials:** Generative AI contributes to innovation by optimizing material properties and discovery techniques.[24] The market for generative AI in material science was projected to grow significantly, from $1.26 billion in 2024 to $1.68 billion in 2025, driven by factors like the need for novel and sustainable materials.[24]
- **Accelerated Molecular Design and Optimization:** Companies are developing accelerated generative AI models for drug discovery and materials science. For example, **Nvidia Corporation's BioNeMo Cloud Service**, launched in March 2023, offers pre-trained and customizable generative AI models, including **AlphaFold2** (for protein structure prediction) and **MoFlow** (for molecular generation).[24] These tools significantly reduce the time and expense for R&D in life sciences and materials discovery by facilitating quicker identification and construction of new therapeutic options and materials.[24]
- **Predictive Analytics and Simulations:** AI-powered predictive analytics are being used to forecast material properties. NVIDIA Modulus, a physics-informed AI platform, enables high-fidelity simulations of physical systems, helping researchers build accurate computational models for materials science faster than traditional methods.[26] Qubit Pharmaceuticals combines quantum computing with AI to model molecular interactions with extreme precision, impacting rational drug design and materials engineering.[26] ORCA AI from the Max Planck Institute is also revolutionizing quantum chemistry simulations for predicting molecular properties.[26]
- **Integration with Additive Manufacturing:** A key trend is the fusion of AI with additive manufacturing processes, allowing for the design and creation of materials with customized properties on demand.[24]

The surge in AI technology investments, with global AI adoption rising substantially, is a major driver for the expansion of generative AI in the materials science market.[24]

3.4. Finance

The finance industry, characterized by vast datasets, complex risk environments, and the need for rapid decision-making, is increasingly leveraging AI for research, development, and operational efficiency.

3.4.1. Financial Modeling and Risk Assessment

AI is enhancing the sophistication and accuracy of financial models and risk assessment processes.

- **Predictive Modeling:** AI adoption in financial modeling enables predictive models that can reveal unseen patterns and revenue drivers, accelerating tasks like company valuation and risk assessment.[33] ML algorithms analyze market trends and credit risk, considering diverse factors like social media activity and transaction history for credit scoring.[33]
- **Dynamic Budgeting and Forecasting:** AI transforms budgeting and forecasting from static quarterly updates to a dynamic, continuous process. Finance teams can adjust budgets and forecasts in real-time based on live data inputs like market trends and revenue fluctuations. AI-driven scenario modeling provides a range of possible outcomes to prepare for contingencies.[34]
- **Enhanced Credit Risk Assessment:** AI brings new levels of accuracy to credit risk assessment by integrating real-time market data with historical financial records. Advanced algorithms evaluate a borrower's creditworthiness by analyzing payment history, industry trends, and even external factors like geopolitical risks, offering dynamic and precise risk scores.[34] For example, SwiftCredit Lending implemented an AI-based credit scoring system that increased approved loans by 40% and reduced default rates by 25% by incorporating alternative data for applicants lacking traditional credit histories.[35]
- **Deep Learning for Complex Analysis:** Deep learning, using multi-layered neural networks, excels in processing unstructured data like news or social media posts for financial market predictions, sentiment analysis, and portfolio optimization.[33]
- **AI-Enhanced Treasury Management:** AI systems analyze cash flow patterns, currency fluctuations, and market data to optimize corporate liquidity management and maximize investment returns. Predictive analytics guide timely decisions on investments or borrowing and streamline foreign exchange exposure management.[34]

The Bank of England's Financial Policy Committee (FPC) noted in April 2025 that AI represents a significant advance over previous modeling techniques, with advanced forms of AI increasingly informing core financial decisions like credit and insurance underwriting.[36] However, the complexity and dynamic nature of some AI models pose new challenges for predictability, explainability, and data integrity.[36]

3.4.2. Fraud Detection and Investment Strategies

AI's ability to analyze vast transactional data in real-time is revolutionizing fraud detection and optimizing investment strategies.

- **AI-Driven Fraud Detection:** Machine learning algorithms monitor patterns across financial transactions, identifying anomalies that signal potential fraud, such as unusual payment locations or abnormal spending trends.[34] These systems can anticipate fraudulent schemes by analyzing evolving threats and historical fraud data. FinSecure Bank, for example, implemented an AI-driven fraud detection system using supervised and unsupervised learning, which reduced fraudulent activities by 60% in the first year and significantly decreased false positives.[35]
- **Optimization of Investment Strategies:** AI technologies are used to analyze and predict

market trends with high precision. CapitalGains Investments developed a proprietary AI platform that analyzed historical price data, economic indicators, and news articles (using sentiment analysis) to predict market movements, achieving a 20% increase in annual returns for clients.[35] EquityPlus Investment saw a 35% increase in portfolio performance metrics by integrating AI for real-time market analysis and dynamic asset allocation.[35] AI models can evaluate risk-return trade-offs, asset correlations, and market conditions to enhance portfolio optimization and maximize returns.[33]
- **Predictive Customer Behavior Analysis:** AI analyzes customer data to predict behavior, preferences, and churn rates, enabling financial institutions to tailor marketing campaigns and improve customer experiences.[33] MetroBank Group used an AI-driven analytics platform to gain a 360-degree customer view, leading to a 30% increase in customer satisfaction and a 20% rise in engagement.[35]

These applications demonstrate AI's capacity to enhance security, optimize returns, and personalize services within the financial sector.

3.5. Manufacturing

The manufacturing industry is undergoing a significant transformation, often referred to as Industry 4.0, with AI playing a central role in creating "smarter factories" and optimizing production processes.

3.5.1. Industrial Automation and Quality Control

AI is driving new levels of automation and precision in manufacturing operations.

- **AI-Driven Robotics and Cobots:** AI-powered robotics and collaborative robots (cobots) are transforming factory floors by automating repetitive, labor-intensive, and dangerous tasks.[37] Cobots work alongside human operators to enhance production speed, consistency, and safety.[37] For example, Amazon uses cobots with ML to optimize operations and accelerate order fulfillment.[38]
- **Automated Quality Assurance:** AI-based computer vision systems inspect products for defects with greater speed and accuracy than human inspectors, ensuring higher consistency and reduced waste.[14] Foxconn, a leading electronics producer, integrated AI and computer vision into its production lines to rapidly detect defects in electronic components, ensuring products meet stringent quality standards.[37] These systems can identify imperfections invisible to the human eye.[16]
- **Assembly Line Optimization:** AI, particularly ML, is used to analyze real-time sensor data and historical performance metrics from assembly lines to improve efficiency, reduce downtime, and enable predictive maintenance.[38] Volkswagen, for instance, uses ML to analyze sensor data to estimate repair needs and optimize assembly operations.[38]

Computer vision allows machines to "see" and interpret their surroundings, enabling more nuanced tasks like object recognition and autonomous navigation on factory floors.[17]

3.5.2. Predictive Maintenance and Supply Chain Optimization

AI's predictive capabilities are crucial for maintaining operational continuity and efficiency in manufacturing.

- **Predictive Maintenance:** AI-driven algorithms analyze real-time data from machinery to predict equipment failures before they occur.[37] This proactive approach lowers maintenance costs, reduces unplanned downtime, and extends the lifespan of machinery.[37] The concept of a "digital twin" – a virtual replica of a physical asset that uses real-time sensor data – is key here, allowing AI to analyze trends, spot abnormalities, and anticipate breakdowns.[38]
- **Supply Chain Optimization:** AI helps manufacturers anticipate demand fluctuations, optimize inventory levels, and streamline logistics.[37] ML algorithms can examine historical data, identify trends, and forecast demand variations with precision.[38] Walmart, for example, integrated AI into its supply chain operations to improve demand forecasting, streamline logistics, and enhance global supply chain resilience.[38]
- **Demand Forecasting and Production Planning:** AI algorithms provide more accurate market demand predictions, helping manufacturers adjust production schedules, minimize excess inventory, and reduce lead times.[37]
- **Energy Management:** AI can analyze energy consumption patterns across production lines and identify areas for improving energy efficiency, thereby lowering costs and reducing carbon footprints without compromising productivity.[37]

McKinsey estimated that Fourth Industrial Revolution technologies, including AI, could generate up to $3.7 trillion in value by 2025, with AI alone potentially contributing $1.2 trillion to $2 trillion in value for manufacturing and supply chain management.[37] This underscores the profound economic impact of AI in this sector.

4. Comparative Analysis of Transformations

While AI's adoption is widespread, the nature and depth of its transformative impact on research methodologies exhibit both commonalities and distinct variations across different fields.

4.1. Similarities in AI Adoption and Impact

Across diverse research domains, several common themes emerge regarding AI's role and benefits:

- **Enhanced Data Analysis Capabilities:** A universal impact of AI is its ability to process and analyze vast and complex datasets far exceeding human capacity.[4] Whether it's genomic sequences in biology [25], textual data in social sciences [11], financial transactions [34], or sensor data in manufacturing [37], AI (particularly ML) enables researchers to extract meaningful patterns, correlations, and insights that were previously inaccessible. This leads to more data-driven decision-making in all fields.[8]
- **Increased Efficiency and Automation:** AI automates repetitive, time-consuming tasks, freeing up researchers to focus on higher-level cognitive activities such as critical thinking, hypothesis generation, and experimental design.[1] Examples include automated literature screening in

systematic reviews [29], code generation [41], image analysis in medical diagnostics [15], and quality control in manufacturing.[37] This automation translates to significant productivity gains and faster research cycles.[8]
- **Acceleration of Discovery and Innovation:** By rapidly analyzing data, generating hypotheses, and simulating experiments, AI significantly accelerates the pace of scientific discovery and innovation.[6] This is evident in the rapid development of new drugs [22], the discovery of novel materials [24], and the improved prediction of complex phenomena like protein folding [23] or market trends.[35]
- **Personalization and Customization:** AI enables more personalized approaches in various research applications. This includes personalized medicine based on individual genetic profiles [5], tailored educational interventions [43], customized financial advice [33], and on-demand production in manufacturing.[37]
- **Improved Accuracy and Reduced Error:** In many applications, AI can perform tasks with higher accuracy and consistency than humans, reducing the likelihood of errors, especially in data-intensive or repetitive processes.[8] This is crucial in fields like medical diagnosis and quality control.

4.2. Differences in Application and Methodological Shifts

Despite these commonalities, the specific AI technologies employed and the nature of the methodological shifts vary according to the unique characteristics and data types of each field:

- **Dominant AI Technologies:**
  - **Medical/Biological Sciences:** Heavily reliant on ML for analyzing large biological datasets (genomics, proteomics), computer vision for medical imaging, and increasingly generative AI for drug discovery and protein design.[5]
  - **Social Sciences/Humanities:** NLP is a cornerstone for analyzing textual data (social media, archives, interviews), while ML is used for survey data analysis and evidence synthesis tools.[11] Generative AI is emerging for drafting and summarizing texts.
  - **Technology/Engineering:** ML for optimizing R&D processes, generative AI for code and design generation, and specialized AI for simulations (e.g., NVIDIA Modulus for physics-informed AI) are prominent.[24] Agentic AI is also a key development for automating complex engineering workflows.[19]
  - **Finance:** ML and deep learning are crucial for predictive modeling, risk assessment, and algorithmic trading. NLP is used for sentiment analysis from news and reports.[33]
  - **Manufacturing:** Computer vision for quality control and robotics, ML for predictive maintenance and supply chain optimization, and AI-driven automation are central.[17]
- **Nature of Data:**
  - Fields like biology and finance deal with massive, often structured or semi-structured quantitative datasets, making ML particularly effective for pattern recognition and prediction.
  - Social sciences and humanities frequently grapple with large volumes of unstructured qualitative data (text, images, audio), where NLP and, increasingly, multimodal AI are

transformative.
  - Engineering and manufacturing rely on sensor data, design specifications, and simulation outputs, requiring a blend of ML, CV, and specialized AI for physical system modeling.
- **Methodological Shifts:**
  - In fields like drug discovery, AI is shifting the paradigm from serendipitous or trial-and-error approaches to more directed, *in silico* design and prediction.[23]
  - In social sciences, AI enables the analysis of social phenomena at unprecedented scales, moving beyond smaller, manually analyzed samples to population-level insights from digital traces.[11]
  - In manufacturing, AI is driving the shift from reactive maintenance to predictive maintenance and from mass production to mass customization and "lights-out" operations.[37]
- **Ethical and Societal Concerns:**
  - While bias, privacy, and accountability are universal concerns, their specific manifestations differ. In healthcare, biased diagnostic AI can perpetuate health disparities.[21] In finance, biased lending algorithms can lead to discrimination.[44] In social sciences, NLP analysis of social media raises privacy and surveillance issues.[11] The dual-use potential of AI in biological research presents unique security risks.[28]

These differences underscore that while AI offers a common toolkit, its effective and responsible integration requires domain-specific adaptation and a nuanced understanding of each field's unique research questions, data landscapes, and ethical imperatives.

5. Benefits and Advantages of AI in Research

The integration of Artificial Intelligence into research workflows has unlocked a plethora of benefits, fundamentally enhancing how scientific inquiry is conducted and accelerating the generation of knowledge. These advantages span increased efficiency, improved data analysis capabilities, and the automation of laborious tasks.

5.1. Enhanced Efficiency and Acceleration of Discovery

One of the most significant impacts of AI in research is its ability to dramatically improve efficiency and accelerate the timeline from hypothesis to discovery.

- **Rapid Data Processing and Analysis:** AI algorithms, particularly those in machine learning, can process and analyze massive datasets orders of magnitude faster than human researchers.[4] This speed is crucial in data-intensive fields like genomics, particle physics, and astronomy, where datasets can be petabytes in size. For instance, AI can sort through vast amounts of scientific information and identify connections that might take months or years to find manually.[46]
- **Streamlined Research Processes:** AI tools automate various stages of the research lifecycle, from literature review and data collection to experimental design and manuscript preparation.[9] Tools like Elicit automate literature reviews by synthesizing key insights from scientific papers, helping researchers refine questions and hypotheses more efficiently.[26] This streamlining

reduces the overall time spent on research projects.

- **Accelerated Hypothesis Generation and Testing:** AI can assist in generating novel hypotheses by identifying previously unseen patterns or correlations in existing data.[6] Furthermore, AI-driven simulations can rapidly test these hypotheses *in silico*, reducing the need for lengthy and expensive physical experiments in some cases.[26] Microsoft Discovery, an enterprise agentic platform, aims to transform the entire discovery process, enabling researchers to collaborate with AI agents for advanced knowledge reasoning, hypothesis formulation, and experimental simulation, significantly speeding up outcomes.[42] Microsoft researchers used this platform to discover a novel coolant prototype in about 200 hours, a process that would typically take months.[42]
- **Faster Innovation Cycles:** By compressing research timelines, AI enables faster innovation cycles. This is particularly evident in drug discovery, where AI has been shown to reduce the initial discovery phase from years to months [22], and in materials science, where AI aids in the quicker design and identification of new materials.[24]

The cumulative effect of these efficiencies is a significant acceleration in the overall pace of scientific discovery and technological advancement.[6]

5.2. Improved Data Analysis, Accuracy, and Novel Insights

AI's analytical prowess extends beyond speed to encompass greater accuracy and the ability to unearth novel insights from complex data.

- **Pattern Recognition in Complex Data:** AI excels at identifying subtle patterns, anomalies, and correlations in high-dimensional and noisy datasets that may be imperceptible to human researchers.[1] This capability is crucial for making sense of intricate biological systems, financial markets, or social dynamics.
- **Enhanced Predictive Accuracy:** Machine learning models, when trained on appropriate data, can achieve high levels of predictive accuracy in various applications, such as forecasting disease outbreaks, predicting material properties, or anticipating market movements.[8] For example, Google DeepMind's AlphaFold accurately predicts protein structures, opening new avenues for understanding diseases.[8]
- **Generation of Novel Insights:** By processing information from diverse sources and identifying non-obvious relationships, AI can help researchers generate novel insights and formulate new theories.[1] AI tools can foster idea generation by providing related keywords, phrases, and summaries of relevant literature.[40] Connected Papers, for instance, produces visual graphs displaying related papers and identifies influential prior works, helping researchers explore new research areas.[40]
- **Data Visualization for Better Understanding:** AI can transform complex data into intuitive visual formats like charts, graphs, and images, highlighting patterns and making it easier for humans to understand complex information and spot errors or opportunities more quickly.[48]
- **Bias Detection and Mitigation (Potential):** While AI can inherit biases, it can also be used to detect and potentially mitigate biases within datasets, ensuring that research findings are more

fair and reliable, provided careful design and oversight.[47]

These improvements in data analysis contribute to more robust, reliable, and groundbreaking research outcomes.

5.3. Automation of Repetitive Research Tasks

Many aspects of the research process involve repetitive and laborious tasks that can consume significant amounts of researchers' time and effort. AI offers powerful solutions for automating these tasks.

- **Literature Search and Management:** AI tools can automate the process of searching for relevant literature, screening abstracts, categorizing papers, and managing citations.[29] Tools like Scite analyze citation context, while Zendy helps sort through vast scientific information.[40]
- **Data Entry and Preprocessing:** AI can automate data entry from various sources and assist in data cleaning and preprocessing, which are essential but often tedious steps in data analysis.[10]
- **Experimentation and Data Collection:** In laboratory settings, AI-powered robots and automated systems can perform experiments, collect data, and monitor conditions with high precision and consistency, 24/7 [[26] (Laila by BioNTech)].
- **Report Generation and Manuscript Preparation:** Generative AI tools can assist in drafting sections of research papers, summarizing findings, checking grammar, and formatting manuscripts according to specific journal guidelines.[5] QuillBot can simplify complex content and summarize lengthy texts, while Paperpal can help overcome writer's block by generating outlines and abstracts.[40]
- **Administrative Tasks:** AI can automate administrative tasks related to research, such as scheduling meetings, managing grants, and tracking project progress, thereby improving overall operational efficiency.[8]

By automating these routine tasks, AI not only saves time and resources but also reduces the potential for human error and allows researchers to dedicate more of their intellectual energy to creative problem-solving and innovative thinking.[3] This shift can lead to a more engaged and productive research workforce.

6. Challenges, Limitations, and Ethical Considerations

Despite the immense potential of AI in research, its adoption and application are accompanied by significant challenges, inherent limitations, and complex ethical considerations that must be carefully navigated. These issues span technical hurdles, operational complexities, and profound societal implications.

6.1. Technical and Operational Challenges

6.1.1. Algorithmic Bias and Fairness

A critical challenge in AI is algorithmic bias, where AI systems perpetuate or even amplify existing societal biases present in their training data.[44]

- **Sources of Bias:** Bias can originate from various stages:
  - **Biased Data:** If training data reflects historical discrimination or lacks diversity (e.g., skewed towards certain demographics), the AI model will learn and replicate these biases.[49] For example, facial recognition models trained predominantly on lighter-skinned individuals may perform poorly on darker-skinned individuals.[50]
  - **Human Influence:** Developers can inadvertently encode their own biases into algorithms through design choices or data labeling.[49]
  - **Lack of Diverse Data/Teams:** Homogeneous development teams may overlook diverse perspectives, leading to biased AI systems.[49]
  - **Feedback Loops:** Biased outputs can create feedback loops that further reinforce and amplify initial biases over time.[49]
- **Consequences in Research:** In research, biased AI can lead to unfair or discriminatory outcomes, such as in medical diagnosis where algorithms might perform differently across racial groups [20], or in social science research where NLP models might perpetuate stereotypes.[11]
- **'Fairness Drift':** A specific concern in clinical AI is 'fairness drift,' where an algorithm that was fair at deployment becomes unfair over time due to changes in the clinical environment or data distributions across subpopulations.[51] This highlights that fairness is not a one-time assessment but requires continuous monitoring.[51]
- **Mitigation Efforts:** Addressing algorithmic bias requires diversifying training datasets, implementing bias detection techniques (e.g., fairness audits), promoting diversity in AI development teams, and embedding fairness as a core design principle.[49] Research is ongoing to develop quantitative definitions of fairness and methods to mitigate bias during pre-processing, in-processing, or post-processing stages.[49] The European Commission guidelines also stress the need to address biases and potential equality and non-discrimination issues.[9]

Ensuring fairness and equity in AI research applications is paramount to avoid perpetuating societal inequalities and to build trust in AI-driven findings.

6.1.2. Transparency and Interpretability (The 'Black Box' Problem)

Many advanced AI models, particularly deep learning systems and large language models, operate as "black boxes," meaning their internal decision-making processes are opaque and difficult for humans to understand.[9]

- **Lack of Explainability:** It is often challenging to determine precisely how an AI model arrived at a specific prediction or decision.[9] This lack of interpretability makes it difficult to debug models, identify sources of error or bias, and validate their reasoning.[9]
- **Trust and Accountability:** The black box nature erodes trust, as users and stakeholders cannot fully understand or scrutinize the AI's logic.[44] This is particularly problematic in high-stakes research areas like medical diagnosis or policy-making, where understanding the rationale behind a decision is crucial for accountability.[9]
- **Challenges for Reproducibility:** The stochastic and unpredictable nature of some generative AI models can make strict research reproducibility difficult, except for very simple tasks.[18]

- **Regulatory Concerns:** The lack of explainability can also pose challenges for regulatory compliance, as many frameworks require transparency in AI decision-making.[18]
- **Research in Interpretability:** Efforts are underway to develop techniques for "explainable AI" (XAI) to make model behavior more transparent.[49] Interpretability research is considered high-risk, high-reward, with the potential to ensure AI is aligned with human values.[53] Anthropic's research, for example, aims to trace the "thoughts" of language models to better understand their internal mechanisms.[53] The Stanford HAI AI Index Report 2025 noted an increase in transparency scores among major model developers, though significant opacity remains in areas like data access and copyright.[54]

Improving the transparency and interpretability of AI models is essential for their responsible adoption in research, fostering trust, and ensuring that their outputs can be critically evaluated and validated.

6.1.3. Data Dependency, Quality, and Security

AI systems, especially machine learning models, are heavily dependent on data for training and operation. The quality, quantity, and security of this data are critical determinants of AI performance and reliability.[4]

- **Data Volume and Diversity:** Generative AI, in particular, often demands massive and diverse datasets from various sources (public, private, synthetic) and in multiple formats (text, images, code).[56] Lack of a clear data architecture to manage this complexity can hinder GenAI strategies.[56]
- **Data Quality ("Garbage In, Garbage Out"):** The accuracy and reliability of AI outputs are directly tied to the quality of the input data. Poor data quality, including errors, inconsistencies, or incompleteness, can lead to flawed models and inaccurate research conclusions.[18] Data cleaning and preprocessing are therefore crucial but often challenging steps.[10]
- **Legacy Data Environments:** Many organizations rely on legacy data systems not designed for the probabilistic models used by modern AI, leading to integration challenges, costly preprocessing, and inefficiencies.[56]
- **Data Privacy and Security Concerns:** AI systems often require access to vast amounts of potentially sensitive data, raising significant concerns about data privacy, security, and compliance with regulations like GDPR.[34] Data breaches or misuse can have severe consequences.[44] The European Commission emphasizes protecting unpublished or sensitive work by not uploading it to external AI systems without assurances against data reuse and ensuring compliance with EU data protection rules when handling personal data.[9]
- **Model Hallucinations and Data Integrity:** Generative AI models can "hallucinate," producing plausible but false or nonsensical information, often due to issues in training data or model overfitting.[9] A July 2024 study found LLM hallucination rates between 20% and 30%.[56] This undermines trust and data integrity.
- **Data Sovereignty and Regulatory Alignment:** The global nature of AI development and data storage creates challenges related to data sovereignty and navigating differing international

regulations concerning data access, transparency, and ethical use.[56]

Addressing these data-related challenges requires robust data governance frameworks, clear data strategies, investment in data quality tools, and stringent security measures.[48]

6.1.4. Cost and Resource Intensiveness (Compute Power, Specialized Hardware)

Developing and deploying advanced AI models, particularly large-scale ones, is a resource-intensive endeavor.

- **High Compute Demand:** AI reasoning, pre-training, post-training, and inference for complex models require substantial computational power.[31] This demand is a major driver for the semiconductor industry.[31]
- **Specialized Hardware:** Efficient AI processing often necessitates specialized hardware like Graphics Processing Units (GPUs) and Application-Specific Integrated Circuits (ASICs).[2] While ASICs offer higher efficiency for specific tasks, GPUs provide greater flexibility.[31] The availability and cost of this hardware can be a barrier.[31]
- **Energy Consumption:** The computational demands of AI translate to significant energy consumption, raising environmental concerns and contributing to operational costs.[58] AI is creating a "tsunami of demand for chips and power".[58]
- **Foundry Constraints:** The manufacturing of advanced chips (foundries) faces constraints due to long development cycles for new facilities and physical limitations, impacting the supply of necessary hardware.[31]
- **Upfront Investment Costs:** The initial investment in AI infrastructure, software, and skilled personnel can be substantial, posing a barrier to adoption, especially for smaller research institutions or companies.[34] High interest rates can exacerbate these financing challenges.[59]
- **Training Costs for Large Models:** Training large foundation models, like LLMs, can cost millions of dollars due to the need for thousands of clustered GPUs and weeks of processing.[2]

These cost and resource challenges can limit access to cutting-edge AI capabilities and may favor larger, well-funded research organizations and corporations.[9]

6.1.5. Skills Gap and Workforce Adaptation

The rapid advancement of AI technologies has created a significant skills gap, as the demand for AI expertise often outpaces the available talent pool.

- **Demand for AI and Data Skills:** Employers increasingly recognize AI and big data skills as "core," with nearly 9 out of 10 reporting their importance is rising.[59] Job postings for AI roles are growing much faster than for other jobs.[10]
- **Shortage of AI Professionals:** There is a high demand for professionals skilled in mathematics, statistics, programming, data handling, and domain-specific AI application.[10] The lack of skilled personnel is a barrier to AI adoption.[34]
- **Need for Upskilling and Reskilling:** As AI automates certain tasks, there is a critical need to upskill and reskill the existing workforce to effectively leverage AI tools and adapt to changing

job roles.[59] Many organizations are offering training to upskill employees on AI tools and reskill those whose jobs are affected by AI.[60]
- **AI Literacy:** A broader challenge is fostering AI literacy across the workforce and general population, ensuring individuals can understand, interact with, and critically evaluate AI systems.[44] There is a lack of consensus on what AI literacy entails, but an urgent need for accessible and scalable opportunities to acquire it.[61]
- **Impact on Critical Thinking:** Over-reliance on AI, particularly GenAI, raises concerns about the potential deterioration of critical thinking skills among knowledge workers, as they may shift from task execution to merely overseeing AI outputs without deep engagement.[43]

Addressing the skills gap requires concerted efforts in education, training, and continuous learning to prepare the workforce for an AI-driven future.[10]

6.2. Ethical and Societal Implications

6.2.1. Privacy, Data Protection, and Confidentiality

The use of AI in research, especially when involving personal or sensitive data, raises profound ethical concerns regarding privacy and data protection.

- **Data Misuse and Unauthorized Access:** AI systems often require access to vast datasets, including personal information, increasing the risk of data misuse, unauthorized access, and breaches.[44] The European Commission guidelines stress that researchers must protect unpublished or sensitive work and ensure compliance with data protection rules like GDPR when handling personal data provided to or generated by AI systems.[9]
- **Training Data Concerns:** Generative AI models are often trained on massive datasets scraped from the internet, which may contain personal information without explicit consent for such use.[9] This raises questions about data ownership and the ethics of using such data for model training.[63] User inputs into AI tools might also be used to further train models, potentially leading to untraceable reuse of data.[9]
- **Opaque Algorithms and Lack of Transparency:** The "black box" nature of many AI algorithms makes it difficult for individuals to understand how their data is being used and what decisions are being made based on it, hindering transparency and accountability.[57]
- **Surveillance and Control:** The application of AI in surveillance, control, and assessment practices (e.g., in education or public safety) can undermine trust and autonomy if not implemented ethically and transparently.[43]
- **Need for Robust Governance and PETs:** Addressing these privacy concerns requires robust data governance frameworks, adherence to privacy-by-design principles, and the use of Privacy-Enhancing Technologies (PETs) like differential privacy and federated learning.[55] Global legal developments, such as the EU AI Act and various state-level privacy laws in the US, are attempting to create frameworks for responsible AI data handling.[57]

Research ethics committees are increasingly tasked with conducting continuous risk assessments and advising institutions on data protection measures, especially concerning novel AI technologies.[65]

6.2.2. Accountability and Human Oversight in AI-Driven Decisions

As AI systems take on more complex decision-making roles in research, questions of accountability and the necessity of human oversight become critical.

- **Responsibility for AI Outputs:** Researchers remain ultimately responsible and accountable for the scientific output and integrity of content generated by or with AI tools.[9] AI systems cannot be designated as authors because authorship implies agency and responsibility that lies with humans.[9]
- **Human-in-the-Loop:** Effective AI integration often requires a "human-in-the-loop," "human-on-the-loop," or "human-in-command" approach, ensuring that human experts can review, validate, and override AI-driven decisions, especially in critical applications.[67] Human oversight is crucial for ensuring accuracy, completeness, and lack of bias in AI-generated content.[66]
- **Legal Liability:** Companies and institutions may be held liable for the mistakes or harms caused by their AI tools, including AI agents.[69] For instance, Air Canada was held liable for incorrect information provided by its chatbot.[69] This underscores the need for clear lines of responsibility.
- **Challenges with Agentic AI:** As AI agents become more autonomous, establishing robust human oversight frameworks is essential to ensure accountability and maintain trust.[69] The reliability of LLMs (prone to hallucinations) and the performance/cost issues of chaining multiple AI agents can compound accountability challenges if not managed with guardrails and human supervision.[69]
- **Governmental Directives:** Governmental bodies are emphasizing the need for agencies to establish clear expectations for appropriate AI use, particularly in consequential decision-making, and to delegate responsibilities and accountability for risk acceptance to appropriate officials.[68] If proper risk mitigation is not possible, the use of high-impact AI must cease.[68]

A balance must be struck between leveraging AI's capabilities and ensuring that human researchers retain ultimate control and responsibility for the research process and its outcomes.

6.2.3. Intellectual Property, Authorship, and Plagiarism

The use of generative AI in creating research content introduces complex issues related to intellectual property (IP), authorship, and plagiarism.

- **Authorship of AI-Generated Content:** The consensus among many publishers and institutions is that AI cannot be an author because it cannot take responsibility for the work's accuracy, integrity, or originality.[9] Authorship requires significant intellectual contribution and accountability, which are human attributes.[66]
- **Disclosure of AI Use:** Transparency is paramount. Researchers are generally required to disclose the use of generative AI in the writing process, detailing which tools were used and how they contributed to the manuscript.[9] This allows readers, reviewers, and editors to understand the role AI played.[66]
- **Intellectual Property of AI Outputs:** Ownership of AI-generated content can be ambiguous and depends on the terms of service of the AI tools used and prevailing copyright laws.[63] Some platforms state users own the output, while others may have different terms.[66]

- **Risk of Plagiarism:** AI models are trained on vast datasets, which may include copyrighted material. There's a risk that AI-generated text could unintentionally replicate existing works without proper attribution, leading to plagiarism.[9] Researchers must ensure the originality of their work and properly cite any sources, including those that may have informed AI-generated portions.[66] Many AI research tools now include plagiarism checkers.[40]
- **Copyright and Training Data:** Ongoing legal cases question the legality of training AI models on copyrighted public content without permission or compensation, which could have significant implications for the future development and use of generative AI.[18]

Navigating these IP and authorship issues requires careful attention to institutional policies, publisher guidelines, and ethical best practices, emphasizing human responsibility and transparency.

6.2.4. Misinformation, Disinformation, and 'Hallucinations'

A significant societal risk associated with generative AI is its potential to create and disseminate misinformation (false information spread unintentionally) and disinformation (false information spread intentionally).

- **AI-Generated Falsehoods ('Hallucinations'):** Generative AI models, particularly LLMs, are known to "hallucinate" – producing outputs that are plausible-sounding but factually incorrect, nonsensical, or disconnected from the input prompt.[9] This can include inventing citations or misrepresenting information from sources.[9]
- **Scale and Persuasiveness:** AI tools make it easier for bad actors to create persuasive, customized disinformation (fake text, images, video, audio) at scale, posing risks to public discourse, elections, and trust in information.[9]
- **Impact on Research Integrity:** In a research context, hallucinations can lead to the inclusion of false data or unsupported claims in scientific literature, undermining research integrity if not diligently verified by human researchers.[9] A study warned that AI-generated summaries of scientific research can overgeneralize findings and exaggerate results.[71]
- **Need for Critical Evaluation:** Users, including researchers, must critically evaluate all AI-generated content, verify facts with reputable sources, and be aware of the limitations of AI tools.[70] The European Commission guidelines emphasize that researchers must maintain a critical approach and verify AI-produced information.[9]
- **Challenges in Detection:** The quality of AI-generated content can make it difficult to distinguish from human-generated content, complicating efforts to combat misinformation.[9]

Addressing the challenge of AI-generated misinformation requires a combination of technological solutions (e.g., improved fact-checking algorithms, watermarking AI content), media literacy initiatives, and responsible development practices by AI creators.

6.2.5. Dual-Use Concerns and Security Risks

AI technologies developed for beneficial research purposes can also have "dual-use" potential, meaning they could be intentionally misused for harmful purposes, particularly in biological and chemical sciences.

- **Development of CBRN Threats:** A primary concern is the misuse of AI models for the development of chemical, biological, nuclear, or radiological (CBRN) threats.[45] AI could lower the barrier for non-experts to design, synthesize, or acquire such weapons by facilitating access to information and automating complex processes.[45]
- **AI in Life Sciences Research:** While AI offers immense benefits in biology (e.g., drug discovery, protein engineering), AI-enabled life sciences research could be misused to engineer or modify pathogens, potentially leading to high-consequence disease outbreaks.[28] Experts have noted that AI protein design models are "vulnerable to misuse and the production of dangerous biological agents".[45]
- **Need for Safety Evaluations:** There is a critical need for robust, standardized evaluations of AI systems, especially biological AI models, to assess and mitigate these dual-use risks *before* model deployment.[45] These evaluations should prioritize capabilities that enable high-consequence risks.[45]
- **Governmental and Institutional Responses:** Multiple national governments (e.g., US, UK) and international bodies have launched efforts to address AI safety, security, and ethics, including the establishment of AI Safety Institutes and frameworks for evaluating frontier AI models.[45] The US National Academies recommended monitoring AI development and strategic data collection to protect against misuse in biotechnology.[73]
- **Cybersecurity Threats:** AI can also be used to enhance cyber threats, such as by developing more sophisticated malware or automating hacking attempts.[1] Conversely, AI is also used to improve cybersecurity defenses.[1]

The responsible development and deployment of AI in research necessitates proactive measures to anticipate and mitigate dual-use risks, including establishing clear ethical guidelines, security protocols, and international cooperation.

6.2.6. Impact on Human Roles and the Nature of Research

The increasing integration of AI into research is fundamentally altering the roles of human researchers and the very nature of scientific inquiry.

- **Augmentation vs. Replacement:** A central theme is whether AI will augment human capabilities or replace human researchers.[21] While AI can automate many tasks, experts generally believe it will enhance human productivity and allow researchers to focus on more creative and complex aspects of research, rather than leading to widespread job loss in the immediate future.[21] The 2025 Human Development Report emphasizes that differences between humans and machines can create powerful complementarities that expand human potential.[75]
- **Shift in Required Skills:** The demand for skills is changing. Routine tasks may be automated, reducing demand for some current skills, while skills related to leveraging AI tools, data analysis, critical thinking, and interdisciplinary collaboration will become more crucial.[59]
- **Evolving Researcher-AI Collaboration:** Future human-AI teaming (HAT) will likely involve more dynamic, bidirectional partnerships where AI can act as a mentor, coach, assistant, or peer.[76]

This requires careful consideration of autonomy levels and responsibility allocation.[76]

- **Ethical Oversight by Humans:** Ethics committees in universities are grappling with how to manage AI considerations, data protection, and the balance between innovation and oversight, emphasizing that human judgment remains essential.[65] AI is seen as a tool that needs to be guided by human values and ethical principles.[75]
- **Concerns about Over-Reliance and Critical Thinking:** There are concerns that over-reliance on AI tools, especially for tasks like writing or information synthesis, could diminish critical thinking skills and opportunities for deep learning if not used thoughtfully.[43] The focus is shifting towards verifying AI outputs and integrating them, rather than just generating them.[62]
- **Public vs. Expert Perceptions:** Surveys reveal a gap between public and expert opinions on AI's impact. Experts are generally more optimistic about AI's benefits for jobs and society, while the public expresses more concern about job displacement and loss of human connection.[74]

The future of research will likely involve a symbiotic relationship between humans and AI, where AI handles data-intensive and repetitive tasks, and humans provide critical thinking, ethical guidance, and creative insights. Ensuring this collaboration is beneficial and equitable is a key challenge.

7. Future Predictions and Expert Outlook (Pre-January 2025 Perspectives)

Forecasting the trajectory of AI in research involves synthesizing expert opinions, institutional viewpoints, and observable technological trends. The period leading up to January 2025 was marked by both excitement about AI's potential and growing awareness of the need for responsible development and deployment.

7.1. Trusted Advisors and Institutional Perspectives

Various organizations and thought leaders offered perspectives on AI's future in research, emphasizing themes of trust, responsibility, and strategic integration.

- **The AI Trust Imperative:** The 2025 Edelman Trust Barometer (reflecting early 2025 sentiment based on 2024 data) highlighted that AI was at an inflection point where trust must be earned.[78] It noted global divides in AI trust (e.g., high in China, lower in the U.S.) and demographic gaps (older adults, lower-income individuals, and women being less trusting).[78] The report stressed that AI leaders who prioritize transparency, fairness, proactive governance, and demonstrated real-world benefits would build durable trust and gain a competitive advantage.[78] Concerns about job displacement and misinformation were significant but seen as surmountable with thoughtful design and strong oversight.[78]
- **Stanford HAI AI Index Report (2025):** This report, based on data up to late 2024/early 2025, predicted continued improvement in AI performance on demanding benchmarks, deeper embedding of AI in everyday life (including healthcare), and recognition of AI's impact on science through top awards.[54] However, it also noted that complex reasoning remained a challenge for AI models and that the responsible AI ecosystem was evolving unevenly, with rising AI-related incidents but rare standardized RAI evaluations among major developers.[54]
- **European Commission:** In its April 2025 guidelines (reflecting earlier understanding), the EC

emphasized the responsible use of generative AI in research, focusing on principles like reliability, honesty, respect, accountability, and transparency.[9] The guidelines addressed risks such as disinformation, IP issues, data protection, bias, and the need for human oversight, advocating for continuous learning and adaptation to the evolving AI landscape.[9]

- **LSE (London School of Economics):** Research from LSE (reflecting pre-Jan 2025 understanding) highlighted that advanced LLMs were still too complex for full explainability and that their stochastic nature challenged research reproducibility.[18] They cautioned against accepting LLM outputs at face value due to "hallucinations" and emphasized the need for independent human verification, alongside concerns about IP and privacy in multimodal AI.[18]
- **National Academies (U.S.):** Reports and discussions from the National Academies (reflecting pre-Jan 2025 views) focused on AI's potential in biotechnology and biosecurity, recommending monitoring and mitigation against misuse for developing harmful biological agents, alongside strategic data collection.[73] They also presented frameworks for trustworthy AI in health and medicine, emphasizing equity, workforce well-being, and stakeholder collaboration.[80]
- **Royal Society (U.K.):** The Royal Society's work on machine learning (reflecting pre-Jan 2025 views) aimed to demonstrate its potential over the next 5-10 years, highlighting opportunities and challenges and the need for careful stewardship.[81] They were also developing policies for disclosing AI use in scientific manuscripts submitted to their journals, adapting to the evolving tools.[82]
- **Industry Consultants (PwC, BCG, Accenture, Infosys, Deloitte, CREO):** These firms generally predicted AI would become a commercial imperative, with increasing integration into device-side architectures and a focus on agentic AI for higher ROI.[58] CREO Consulting anticipated multimodal AI becoming standard, AI reshaping education, and advanced reasoning becoming the competitive battleground, while AI safety concerns would grow.[58] Deloitte highlighted data and model quality challenges for GenAI, including the need for clear data architecture and managing model opacity.[56] PwC projected AI could contribute up to $15 trillion to the global economy by 2030.[83]

A common thread is the recognition of AI's transformative power coupled with an urgent call for ethical frameworks, transparency, and robust governance to ensure its benefits are realized responsibly.

7.2. Evolution of Human-AI Collaboration in Research

The future of research is increasingly envisioned as a collaborative endeavor between humans and AI, moving beyond AI as a mere tool to AI as an active partner.

- **AI as an Augmentative Force:** Many experts and institutions predict that AI will primarily augment and enhance human capabilities rather than replace them entirely.[61] The focus is on leveraging AI to handle routine, data-intensive tasks, thereby freeing human researchers for more complex cognitive work, creativity, and critical thinking.[59]
- **Dynamic Human-AI Teaming (HAT):** The National Academies' discussions on HAT (reflecting pre-Jan 2025 views) explored a future where interactions are more dynamic and bidirectional,

with AI potentially playing roles as mentor, coach, assistant, or peer.[76] Key questions revolve around appropriate autonomy levels for AI, the allocation of responsibilities between humans and AI, and designing AI teammates that genuinely enhance human decision-making and performance.[76]

- **Agentic AI and Workflow Integration:** The rise of agentic AI, where AI systems can autonomously perform complex, multi-step tasks and coordinate efforts, is a significant trend.[2] Platforms like Microsoft Discovery aim to enable researchers to collaborate with a team of specialized AI agents to drive scientific outcomes.[42] This suggests a future where research workflows are orchestrated by human researchers guiding teams of AI agents.
- **Shifting Human Roles:** As AI takes over more analytical and operational tasks, the role of the human researcher will likely shift towards defining research questions, designing ethical frameworks, interpreting complex or ambiguous results, ensuring the validity of AI-generated findings, and communicating research to broader audiences. The LSE source suggests a shift in prompting, with researchers providing careful instructions and context to more capable "reasoner" models.[18]
- **Need for New Skills:** Effective human-AI collaboration will necessitate new skills for researchers, including AI literacy, prompt engineering, data interpretation in the context of AI outputs, and the ability to critically evaluate and manage AI systems.[59]

The overarching goal is to create a synergistic relationship where the distinct strengths of humans (e.g., creativity, intuition, ethical judgment) and AI (e.g., speed, scale, pattern recognition) are combined to achieve research outcomes that neither could accomplish alone.[75]

7.3. Advancements in AI Capabilities for Scientific Discovery

AI technology itself is predicted to continue its rapid evolution, leading to even more powerful tools for scientific discovery.

- **Improved Reasoning and Problem-Solving:** A key area of development is enhancing AI's reasoning capabilities, moving beyond pattern recognition to more human-like "thinking" through complex problems.[18] Models like Google's Gemini 2.5 Pro and OpenAI's o1 were early indicators of this trend.[18] CREO Consulting predicted advanced reasoning and cognitive emulation would be the competitive battleground for sophisticated AI.[58]
- **Sophisticated Multimodal AI:** The integration of different data modalities (text, image, audio, video) into single AI models is expected to mature, allowing for more holistic and context-aware analysis.[7] This will enable AI to tackle research questions that require understanding complex, multi-faceted data.
- **More Capable Agentic Systems:** AI agents are predicted to become more autonomous and capable of orchestrating complex workflows, potentially managing entire research sub-projects under human guidance.[2]
- **Domain-Specific Foundation Models:** While general-purpose foundation models will continue to advance, there will likely be an increasing focus on fine-tuning these models or developing new ones specifically for scientific domains (e.g., BioNeMo for biology and chemistry) to achieve

higher performance and relevance.[24]

- **AI-Generated Scientific Publications:** Sakana AI predicted that future generations of "AI Scientist" systems would be capable of generating entire peer-reviewed scientific papers, potentially at or beyond human levels, raising profound questions for the scientific publishing process.[84]
- **Accelerated Discovery in Specific Fields:** Tools like BenevolentAI (drug discovery), AlphaFold-Multimer (protein interactions), Elicit (literature reviews), and NVIDIA Modulus (simulations) are expected to continue shaping hypothesis generation, molecular modeling, and data analysis across various scientific disciplines.[26]

While the Stanford HAI report noted that complex reasoning remains a challenge [54], the overall trajectory points towards AI systems that are increasingly powerful, versatile, and integrated into the fabric of scientific discovery.

7.4. Philosophical Implications for Knowledge Advancement and Critical Thinking

The rise of AI in research carries profound philosophical implications for how knowledge is created, validated, and understood, as well as for the role of human cognition, particularly critical thinking.

- **Nature of Understanding and Learning:** AI's ability to process information and generate insightful responses challenges traditional distinctions between human and machine-based learning.[43] While AI can efficiently analyze data, it may lack the nuanced understanding, creativity, and real-world contextual awareness inherent in human cognition.[43]
- **Impact on Critical Thinking Skills:** A significant concern is the potential for over-reliance on AI tools to diminish human critical thinking skills.[43] If researchers or students passively accept AI outputs without rigorous scrutiny, or use AI to bypass deep engagement with material, their ability to think critically, solve problems independently, and develop nuanced judgments may atrophy.[43] Microsoft research indicated that higher confidence in GenAI is associated with less critical thinking, and that GenAI shifts the nature of critical thinking towards information verification and response integration rather than primary generation.[62]
- **Redefining Knowledge and Truth:** As AI generates increasingly sophisticated and plausible content, questions arise about the nature of knowledge and truth. The tendency of AI to "hallucinate" or generate fake citations necessitates a heightened skepticism and rigorous verification processes.[18] This may lead to a re-evaluation of what constitutes reliable evidence and how knowledge claims are substantiated.
- **The Role of Human Agency in an AI-Driven World:** The 2025 Human Development Report (UNDP) emphasizes that it is people, not machines, who determine how technologies are used and whom they serve.[75] AI acts as a mirror, reflecting and amplifying societal values and inequalities. This calls for conscious choices in AI design and deployment to ensure it expands human potential and promotes equity, rather than eroding freedoms or deepening divides.[75]
- **Ethical AI and Human Values:** Ensuring that AI development aligns with human values is a core philosophical and practical challenge.[53] Transparency and interpretability are key to checking this alignment and building trust.[53] The development of AI ethics and governance frameworks is

crucial to guide AI's integration into society and research responsibly.[61]

The integration of AI into research is not just a technological shift but also a cognitive and philosophical one, prompting a re-examination of how we learn, think, create knowledge, and define human expertise in an increasingly AI-mediated world. A balanced approach, fostering human-AI collaboration while safeguarding critical human skills and ethical principles, will be essential.

8. Conclusion

The integration of Artificial Intelligence into modern research represents a watershed moment, fundamentally reshaping methodologies, accelerating discovery, and expanding the frontiers of knowledge across virtually all academic disciplines and industrial sectors. The capabilities offered by core AI technologies like Machine Learning, Natural Language Processing, Computer Vision, and Generative AI, augmented by advancements in multimodal systems and reasoning, have unlocked unprecedented efficiencies in data analysis, automated laborious tasks, and enabled the generation of novel insights at a scale and speed previously unimaginable.

8.1. Synthesizing the Transformative Role of AI

From the rapid design of life-saving drugs and the detection of diseases with enhanced accuracy in the medical sciences, to the analysis of complex social phenomena from vast textual datasets in the humanities, and the optimization of industrial processes in manufacturing and finance, AI's impact is pervasive and profound. It has enabled researchers to tackle problems of greater complexity, personalize interventions, and push the boundaries of innovation. The comparative analysis reveals common threads of enhanced data-driven decision-making and accelerated research cycles, even as the specific applications and methodological shifts are tailored to the unique data landscapes and questions of each field. The promise of AI lies not just in doing existing research faster, but in enabling entirely new forms of inquiry and discovery.

8.2. Balancing Innovation with Responsibility

However, this transformative potential is accompanied by significant challenges and ethical imperatives. Algorithmic bias, lack of transparency in AI decision-making, data privacy and security vulnerabilities, the high cost and resource demands of AI development, and an emerging skills gap are critical hurdles that require careful management. Furthermore, societal implications concerning intellectual property, the potential for misinformation and dual-use, accountability for AI-driven decisions, and the evolving role of human researchers demand proactive and thoughtful consideration. The tendency for AI to "hallucinate" underscores the non-negotiable need for human oversight and critical evaluation in all research applications.

Expert opinions and institutional perspectives leading up to early 2025 consistently emphasized the necessity of building trust in AI through transparency, fairness, and demonstrated real-world benefits. The development of responsible AI frameworks and ethical guidelines is paramount to ensure that these powerful technologies are deployed in a manner that is equitable, safe, and aligned with human values.

8.3. The Path Forward for AI in Research

The future trajectory of AI in research points towards increasingly sophisticated human-AI collaboration. AI is expected to evolve from a tool to an active partner, with advancements in reasoning, multimodal understanding, and agentic capabilities enabling AI systems to take on more complex and autonomous research tasks under human guidance. This evolving partnership will necessitate a continuous adaptation of skills within the research community, fostering AI literacy and critical engagement with AI-generated outputs.

Philosophically, AI challenges us to reconsider the nature of knowledge, the process of discovery, and the essence of human critical thinking. The path forward requires a deliberate and balanced approach: one that enthusiastically embraces AI's capacity to augment human intellect and accelerate scientific progress, while simultaneously instilling robust safeguards, ethical principles, and a commitment to human agency. By fostering a research ecosystem where innovation and responsibility advance in tandem, the global community can harness the full transformative power of AI to address humanity's most pressing challenges and unlock a future of unprecedented discovery.

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