Big Data and AI Economic Analysis

Measuring Technological Progress in Real Time with ArXiv

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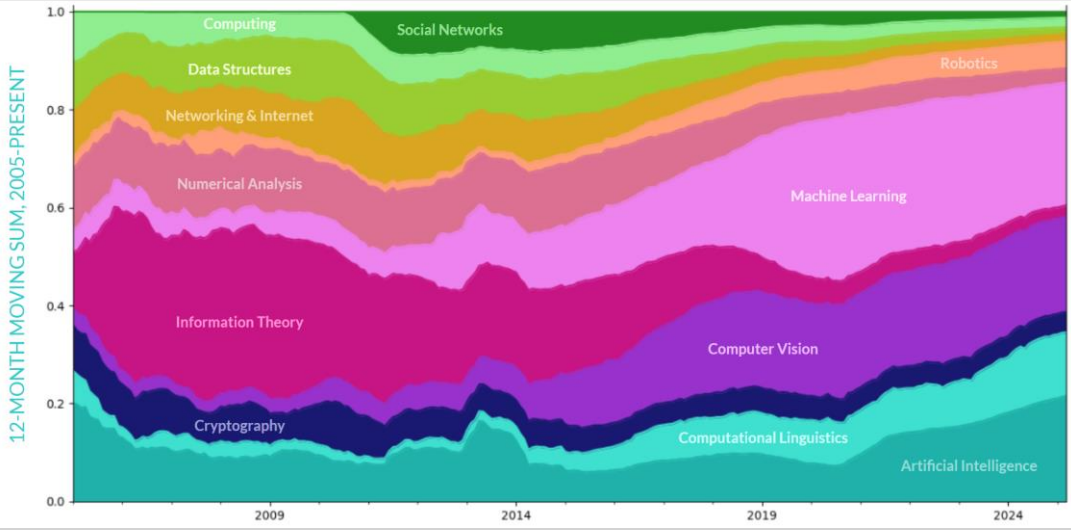
Key Messages

- **Understanding the process of science creation is key to monitoring the rapid digital transformation**. Using natural language processing techniques (NLP), at BBVA Research we have developed a new set of technological indicators using data from *arXiv.org*, a well-known open-access preprint repository.
- Our monthly indicators track arXiv preprint publications in computer science, physics, and mathematics to deliver a **granular and real-time signal of research activity, thus of technological progress and digital transformation**. These metrics highly correlate with traditional proxies of research activity such as patents.
- Computer science preprints have exploded from under 10% of all arXiv submissions in 2010 to nearly 50 % in 2025, driven predominantly by **AI research now representing about 70% of all computer science output**. Conversely, research on physics and math (at both aggregate and subfield level) has grown at a steady rate.
- **There was a turning point in the computer science paradigm around 2014**, with the research focus drastically moving from classic computing theory (e.g. information systems, data structures and numerical analysis) to AI-related disciplines (machine learning, computer vision, computational linguistics and others). Research on cryptography and security was the only subfield essentially unaffected by the AI boom.
- Scientific innovation plays a crucial role in **shaping productivity trends, labor market dynamics, capital flows, investment strategies, and regulatory policies**. These indicators provide valuable insights into our rapidly evolving world, enabling early detection of technological shocks and informing strategic investment decisions.

Graph 1. **RELATIVE EVOLUTION OF THE TOP 10 COMPUTER SCIENCE SUBFIELDS IN ARXIV.ORG***



*Volume of each computer science subfield relative to the aggregate volume of all 10 subfields
Source: BBVA Research with arXiv.org data

The Need for High-Frequency, High-Granularity Signals of Research Activity

In a hyperconnected era defined by rapid technological change, the ability to monitor scientific progress in real time has become increasingly critical to **detect disruptions affecting the economy, society and the financial markets**. This real-time insight not only supports timely and evidence-based decision-making in public policy and investment, but also enriches these fields by providing a deeper understanding of emerging trends, facilitating anticipation of technological shifts and enabling more agile strategic responses. Traditional proxies such as patents, R&D expenditure or researcher job vacancies suffer from lag effects, low reporting frequency—tipically annually or quarterly—and limited granularity. This creates a gap in our understanding of exactly when and where disruptive technological breakthroughs occur. BBVA Research proposes a novel approach to bridging this gap: using **arXiv preprints as a high-frequency, high-resolution indicator of technology research activity**, particularly within the domains of computer science, physics, and mathematics.

Preprints are scholarly manuscripts made publicly available before they have been peer-reviewed and published in an academic journal. Publishing preprints is an established practice among researchers in all disciplines to claim authorship of inventions, receive early feedback, and gain visibility**.** In fact, it is estimated that journal and conference publications that were previously submitted to arXiv gain on average 21,1 (±17,4) more citations in the first 5 years [1]. Additionally, preprint submission prevents important findings from becoming worthless by the time of formal publication. A study revealed in 2022 that the rapid dissemination of knowledge via preprints during the COVID-19 pandemic enabled saving multiple lives [2]. This showcases the importance of quick knowledge dissemination during the fast-changing times we are living. But the advantages of preprints go still further: by capturing results before formal publication, preprints allow us to track the pulse of technological progress in real time. Unlike patents, which often involve considerable periods (generally months or even years) before becoming publicly accessible, preprints provide a real-time, high-resolution view of emerging scientific advancements. This timeliness makes them particularly valuable for anticipating technological shifts and informing forward-looking analyses.

arXiv, a preprint server established in 1991, has become the **de facto repository for early-stage scientific output in computer science, physics and mathematics**. According to Dimensions[1], as of 2025, 91% of all-time preprints in these fields have been archived here [3]. Not only that, but arXiv constitutes the main publication source among all publication types —including journal articles, conference proceedings and books[2] (see Annex 1). Its strength lies in three key pillars: (1) it is open-source, providing free scientific content to more than 5 million users every month [5]; (2) its basic moderation process, which guarantees certain content quality standards without requiring formal peer-review [6]; and (3) it is home to highly influential inventions[3].

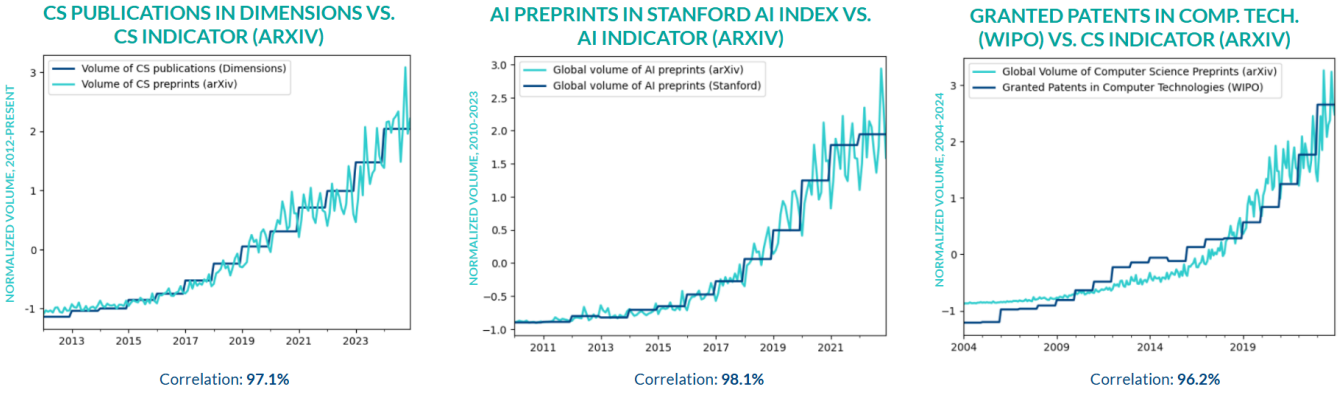
1: Dimensions is a comprehensive, interlinked bibliographic database and analytical tool that connects research data (including publications, grants, clinical trials, patents, and policy documents). For more information, visit https://www.dimensions.ai/.
2: Submitting early to arXiv rarely excludes from publishing on journals and conferences (there are exceptions where certain journals or conferences may forbid preprints). A study showed in 2017 (half a decade before the GenAI boom) that more than 60% of machine-learning conference papers were already on arXiv [4].
3: For example, works such as *Attention Is All You Need* (Google, 2017) [7], which introduced Transformers —the basic architecture on which all current generative AI models are based; the *GPT-4 Technical Report* (OpenAI, 2023) [8]; or the solution to the Poincaré conjecture (Perelman, 2002) [9][10][11], one of the seven Millennium Prize problems [12]—famous for their difficulty and $1 million rewards—, were all first published in arXiv.

Building 129 Technological Research Activity Indicators

To harness arXiv's potential as a technological progress barometer, BBVA Research constructed **129 monthly Tech Research Activity Indicators—40 in computer science, 51 in physics, and 38 in mathematics and statistics**—, each corresponding to an arXiv category [13]. This is done by iteratively scraping publication volume data across category-specific monthly preprint lists from *arxiv.org*. More precisely, lists[4] are extracted in text via iterative HTTP GET requests to the website, such that all lists for all months (January to December, from 1991 to the present) in all 129 arXiv categories are collected. With this data, natural language processing (NLP) techniques are used to count the number of publications in each list text, resulting in multiple time series (one for each category) representing the monthly volume of specialized preprints, a proxy for technological research activity.

Validation against external data sources confirms the robustness of the indicators constructed with arXiv data. Our aggregate computer science (CS) indicator—which combines all computer science subfield indicators—shows a 97,1% correlation with overall computer science publication counts from Dimensions[5] [14] and a 96.2% correlation with computing-related patent grants recorded by the World Intellectual Property Organization (WIPO)[6] [16]. On the other hand, our artificial intelligence (AI) indicator shows a 98.1% correlation with AI preprints tracked by the Stanford AI Index[7] [17]. These high correlation levels not only validate the reliability of our methodology but also underscore its value. Compared to the traditional benchmarks commented before, which suffer from significant time lags, arXiv preprints offer a high-frequency, near-real-time lens into emerging technological trends. As such, they function as a leading indicator, enabling earlier detection of shifts in the direction and intensity of technological progress.

Graph 2. **VALIDATION OF BBVA RESEARCH ACTIVITY INDICATORS WITH EXTERNAL DATA SOURCES**



Source: BBVA Research with arXiv.org and Dimensions data

Source: BBVA Research with arXiv.org and Stanford data

Source: BBVA Research with arXiv.org and WIPO data

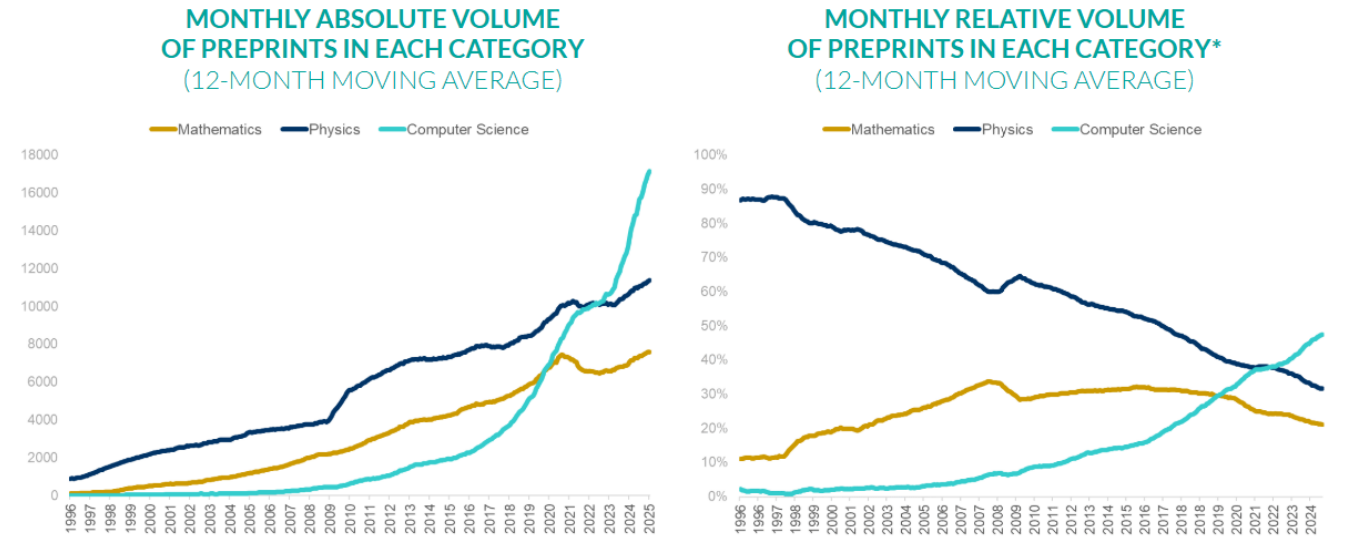
4: As an example, "https://arxiv.org/list/cs.CL/2025-04" corresponds to the URL of the public arXiv list of preprints in Computation and Language (Computer Science) published in April 2025.
5: According to Singh et al. (2021), Dimensions is the most exhaustive among the three most widely-used bibliographic databases worldwide (World of Science, Scopus and Dimensions) with 73,966 indexed journals, in contrast to Scopus' 39,758 and World of Science's 13,610 as of 2021 [15].
6: The World Intellectual Property Organization (WIPO) is the United Nations agency that promotes and protects intellectual property (IP) across the world by cooperating with countries as well as international organizations. For more information, visit https://www.wipo.int/portal/en/.
7: The Stanford AI Index is an annual report created by the Stanford Institute for Human-Centered Artificial Intelligence (HAI) that tracks, collects, and visualizes data related to artificial intelligence. Its mission is to provide unbiased, globally sourced data to help policymakers, researchers, and the general public understand the complex field of AI. For more information, visit https://hai.stanford.edu/ai-index/2024-ai-index-report.

The Exponential Growth in Computer Science, Driven by Disruptive Innovations in Artificial Intelligence

The constructed Research Activity Indicators reveal interesting insights, including the striking acceleration in computer science research over the last decade, as seen in Graph 3. While research on physics and mathematics both increase at a constant rate, the absolute **volume of computer science preprints has experienced an exponential growth**. On a relative basis, its share of total arXiv preprints has increased from under 10% in 2010 to nearly 50% in 2025, reaching a tipping point of surpassing physics—which has led arXiv since its creation in the 90s—around 2021.

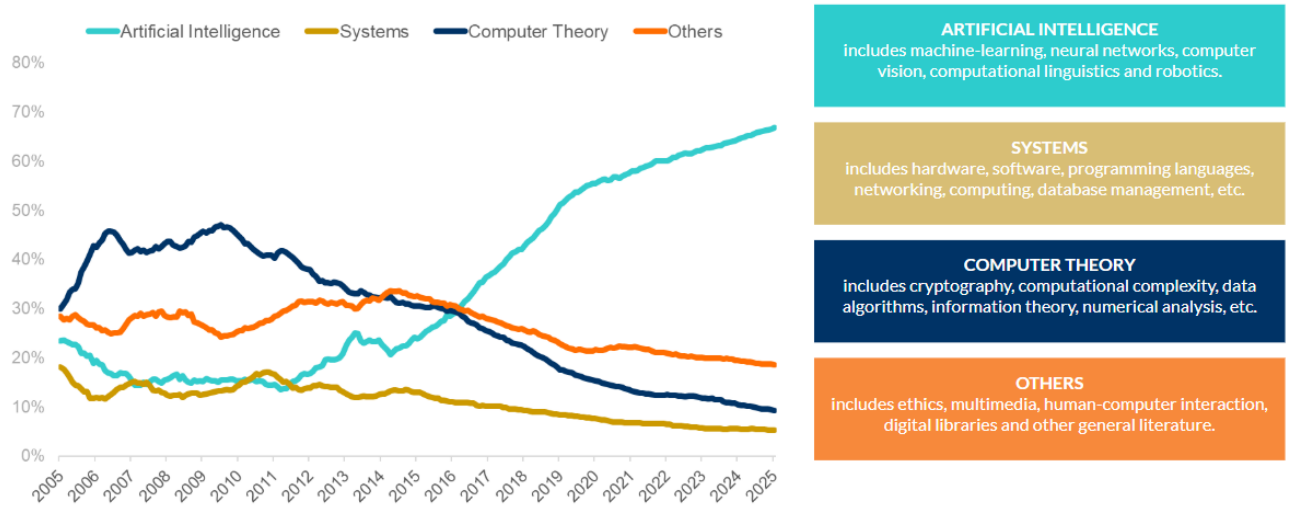
Within computer science, Graph 4 shows that **artificial intelligence (AI)**—encompassing the subfields of machine learning, neural networks, computer vision, computational linguistics, robotics and other general AI—receives the most research interest, **now accounting for almost 70% of all computer science preprint publicatio**n.

Graph 3. **ABSOLUTE AND RELATIVE EVOLUTION OF PREPRINTS IN MATHEMATICS, PHYSICS AND COMPUTER SCIENCE**



*Volume of mathematics, physics and computer science preprints relative to the aggregate volume of preprints in all three categories
Source: BBVA Research with arXiv.org data.

Graph 4. **Relative Evolution of Each Computer Science Topic[8]** (12-Month Moving Average)



Source: BBVA Research with arXiv.org data.

Delving deeper into the dynamics of computer science research, we can see major **inflection points in arXiv volumes concurring with landmark innovations** in their corresponding subfields. Graph 5 shows that:

- **Early peak and steady decline of traditional areas**: Fields like Information Theory (fuchsia), Numerical Analysis (salmon pink), Networking and Internet Architecture (ocher) and Data Structures and Algorithms (pistachio green) held a more prominent share prior to 2014, but have declined in relative importance with the rise of AI-related fields since then.
- **The social-media boom of 2010**. The launch of Instagram [18] and Pinterest in 2010 [19], as well as Snapchat in 2011 [20], coincides with a sharp rise in Social and Information Networks (dark green), growing from near-zero interest before 2010 to becoming a fully-established research field only a year later.
- **Dominance of AI-related fields in recent years**: Since 2014, there's been a notable and sustained surge in the relative volume of Machine Learning (lilac), Computer Vision and Pattern Recognition (purple), Computation and Language (light turquoise), Robotics (salmon) and Artificial Intelligence (dark turquoise), which now represent the largest share among the top 10 subfields. This growth corresponds closely with major technological milestones. The release of the Microsoft Common Objects in Context (COCO) dataset[9] in May of 2014 [21] and the invention of the Inception architecture[10] in September of the same year [22]; as well as latter developments such as the introduction of Transformers[11] in 2017 [7], BERT[12] in 2018 [23] and PyTorch[13] in

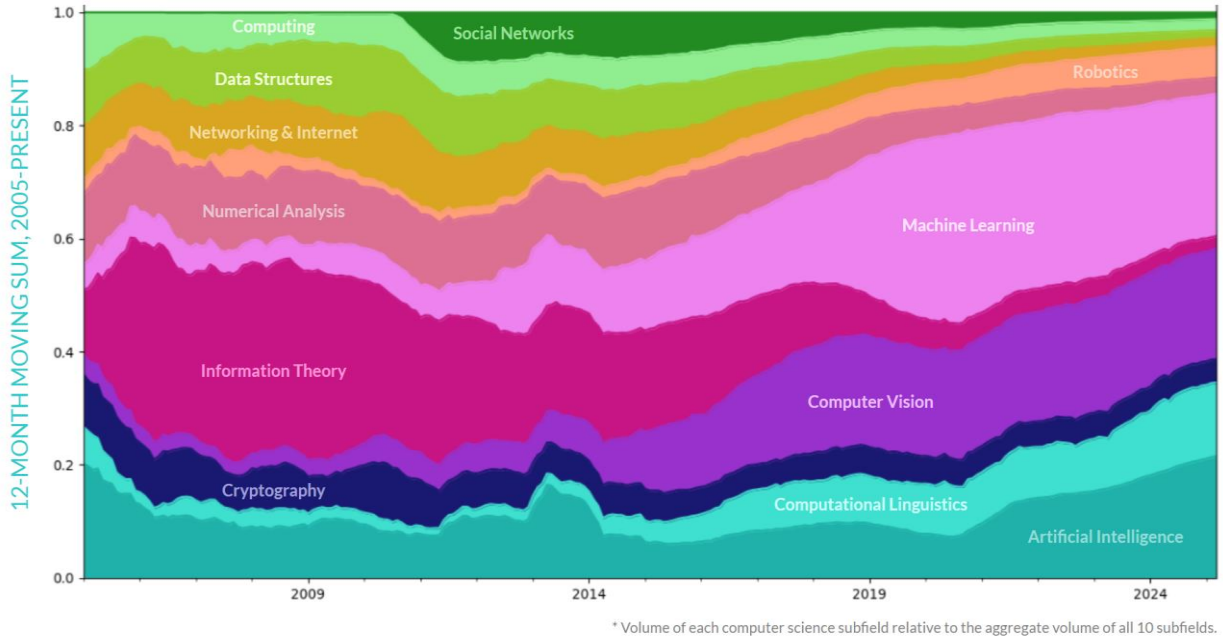
8: Topic groups were created aggregating multiple subfield indicators as follows: Artificial Intelligence (cs.AI + cs.LG + cs.RO + cs.CV + cs.CL + cs.NE + cs.MA), Systems (cs.DC + cs.NI + cs.OS + cs.PL + cs.SE + cs.PF), Computer Theory (cs.CR + cs.IT + cs.CC + cs.DS + cs.DM + cs.FL + cs.CG + cs.GR + cs.GT + cs.NA + cs.MS) and Others (all remaining CS subfields).
9: The largest dataset of real-world images with complex object annotations of the time.
10: The paper *Going Deeper with Convolutions* by Szegedy et al. showed how factorized convolutions could drastically reduce computational cost while improving performance in image recognition.
11: By discarding recurrence and convolutions in favor of *pure attention* mechanisms, the Transformer architecture dramatically simplified sequence modeling while improving performance. This not only revolutionized natural language processing but also opened the door for massive, highly parallelized models.
12: BERT introduced a pre-training technique using *masked language modeling and bidirectional transformers*, drastically improving performance across a wide range of natural language processing (NLP) tasks. Its success popularized the "pre-train, fine-tune" paradigm, now central to modern NLP.
13: Still today's major Python package for deep-learning modeling and deployment.

2019 [24] marks a dramatic rise in artificial intelligence (and its subfields) interest. More recently, OpenAI's GPT-3 model [25] aligns with another spike, emphasizing the revolutionary impact of large language models.

- **Lasting interest in cryptographic research**. Despite the broad leadership of AI-related research in the last decade, the field of Cryptography and Security (dark blue) has never lost its rhythm. Its enduring prominence demonstrates that, at every stage of technological evolution, safeguarding data and communications remains important. In fact, the very AI breakthroughs reshaping industries today only amplify our need for robust, resilient security infrastructures —fueling cryptographic research to outpace emerging threats.
- **Increased concentration**: Graph 5 shows a diversification of research interests up to 2014, after which consolidation around AI-related fields begins. The sharp increase in AI currently dominates the landscape, possibly at the expense of slower-growing areas.

This visualization reinforces the role of arXiv preprints as a **leading indicator** of research trends. The field's evolution clearly anticipates major industry breakthroughs by one-two years or more, often preceding widespread adoption or commercial product development.

Graph 5. **RELATIVE EVOLUTION OF THE TOP 10 COMPUTER SCIENCE SUBFIELDS IN ARXIV.ORG***



*Volume of each computer science subfield relative to the aggregate volume of all 10 subfields
Source: BBVA Research with arXiv.org data

Economic Implications and Future Outlook

The rapid expansion of AI research has relevant implications for productivity dynamics, labor market structures, capital flows, investment strategies and, as such, regulatory frameworks. In this context, real-time indicators derived from preprints offer a promising tool for anticipating and interpreting technology-driven shocks. For central banks and economic policymakers, our indicators could serve as early warning systems for technological shocks, enabling timely assessments of potential impacts on GDP, employment, and inflation expectations. For investors, they provide a forward-looking perspective on the innovation cycle, helping to identify emerging technologies with high

growth potential and guiding strategic capital allocation toward frontier sectors. Notably, cryptography has retained a steady research interest throughout the entire history, even as paradigm-shifting technologies such as AI surge. This stability amid technological disruptions suggests that investment in cryptographic technologies represents a prudent and forward-looking allocation.

Despite their potential, preprint-based indicators also present methodological challenges. The absence of formal peer review introduces heterogeneity in the quality and scientific rigor of submissions. However, it is important to note that arXiv enforces a basic quality control: submissions are screened by expert moderators to ensure relevance to the subject area and compliance with submission guidelines (including checks for plagiarism, offensive content, excessive self-citation, etc.) [6].

As future research, this analysis could be complemented with other preprint platforms (e.g., SSRN, Research Square, Preprint.org), applying citation or download-weighted metrics to account for research impact. Additionally, the described methodology could be extended beyond computer, mathematical and physical sciences into others such as economics and social sciences, broadening its relevance for macroeconomic analysis.

5. Conclusion

This report demonstrates the value of **arXiv preprints as a high-frequency, high-resolution proxy for tracking forefront technological research**, particularly in the fields of computer science, physics and mathematics. By constructing and validating 129 monthly Research Activity Indicators, BBVA Research introduces a novel data-driven approach to anticipate technological trends that traditional proxies, such as patents or R&D expenditure, fail to capture in a timely and granular way.

Empirical validation against external benchmarks (Dimensions, WIPO, Stanford AI Index) reveals that BBVA Research indicators exhibit significantly high correlations (above 96%) with these well-known measures of research and innovation activity. This confirms the robustness of the methodology and underscores its utility for both real-time monitoring and forward-looking economic analysis.

The findings point to a paradigm shift in scientific research dynamics. Computer science, once a marginal share of arXiv submissions, now dominates the platform, with nearly 50% of all preprints by 2025, largely driven by explosive growth in AI-related research. Notably, the timing of submission spikes aligns with breakthrough innovations, such as the launch of deep learning architectures and GPT models, highlighting arXiv's sensitivity to technological inflection points and innovation cycles.

From a macroeconomic perspective, these indicators may act as early-warning systems for technology-induced shocks that may affect GDP, labor markets, inflation, or capital allocation, becoming a relevant tool for central banks, investors, and policymakers.

Future research could enhance both precision and scope. Integrating complementary preprint repositories (e.g., SSRN, bioRxiv) and weighting activity by citations or downloads could increase representativeness.

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Annex

Table 1. **MAIN PUBLICATION SOURCE PER RESEARCH CATEGORY, AS OF MARCH 21ST 2025**

Research Category	First Source	Second Source	Third Source	Forth Source
Computer Science	**arXiv (733.479)**	Lecture Notes in Computer Science (559.479)	IEEE Access (69.807)	Communications in Computer and Information Science (58.466)
Economics	SSRN Electronic Journal (224.004)	Value in Health (58.945)	**arXiv (38.744)**	The Economic Journal (19.102)
Electrical Engineering	Proceedings of SPIE (448.077)	**arXiv (93.148)**	IFAC-PapersOnLine (77.105)	Electronic Letters (49.091)
Mathematics and Statistics	**arXiv (948.121)**	Physical Review D (54.636)	Journal of the Franklin Institute (52.544)	American Mathematical Monthly (48.122)
Physics	**arXiv (1.231.515)**	Proceedings of SPIE (452.763)	Journal of Physics Conference Series (200.674)	Physical Review B (198.626)
Biology	Journal of Biological Chemistry (175.783)	bioRxiv (171.908)	PLOS ONE (110.144)	Biochimica et Biophysica Acta (96.288)
Finance	SSRN Electronic Journal (134.419)	**arXiv (15.976)**	The Journal of Finance (11.999)	The Journal of Economic History (10.981)

Source: Dimensions.ai on March 21st, 2025.

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