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Definition of the research and innovation field of "Artificial Intelligence" and approaches to determining quality

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Summary

In the race for international leadership in the field of artificial intelligence, China has been in first place for years - both in terms of the number of AI research contributions and of citations. Since the publication of ChatGPT at the end of 2022 at the latest, this contradicts the general impression that the main AI innovations are currently coming from the USA rather than China, as well as the general assessment that German and European research is also making important contributions to the AI development. One reason for this divergence is the fact that AI is a very heterogeneous field of research and innovation that consists of different technologies, methods and applications. A standardized definition does not yet exist. However, adequate research field definitions are essential for country comparisons based on bibliometric and patent analyses.

This discussion paper is intended as a contribution to the definition of the research and innovation field of "artificial intelligence" and to the question of the extent to which AI technologies can be classified as "advanced" or "less advanced". This is because the development of this field of research is very dynamic and is characterized by leaps in innovation. The nature of these changes can only be understood by taking a closer look at the technologies themselves which in turn contributes to a better understanding of the bibliometric figures.

To answer the research questions, eight relevant bibliometric studies and the currently best-known classification scheme for machine learning (ML) systems are first analyzed. At the same time, information is collected to answer the question of quality levels. In addition to the literature review, the structures of AI textbooks and AI degree programs were analyzed. And a total of 18 expert interviews were conducted between March and September 2024 with the aim of gaining a deeper understanding of the research subject and its historical development.

As a result, this study presents its own keyword list with 19 main entries and 72 subentries, which reflects the current status of the research and innovation field of AI. The list represents a synthesis of the studies examined, as it was found that none of the existing lists fully cover the field of research as it currently presents itself. Our own keyword list covers both the established AI research areas (symbolic AI) and the machine learning-based research fields that are currently in the foreground (statistical AI). It also takes into account central application fields of AI, such as robotics, automation, facial recognition or machine translation, which are also important for the development of AI technologies in addition to basic research. With regard to the question of the quality levels of AI technologies, specific combinations of keywords from the list can be used for further analyses.

The research shows that generative AI and large language models are currently the most advanced areas of AI research. The development of large language models requires extensive know-how, enormous computing capacities and the processing of enormous amounts of data. However, according to the conclusion of the discussion on approaches to determining quality levels, the current dominance of language models should not obscure the fact that the older AI research areas, which are now referred to as good-old-fashioned AI (GOFAI), also contribute to progress and should therefore be given appropriate consideration when comparing national research profiles and performances.

Summary in German

Im Wettlauf um die internationale Führungsrolle im Bereich „Künstliche Intelligenz" liegt China seit Jahren auf Platz 1 – und zwar sowohl im Hinblick auf die Anzahl der KI-Forschungsbeiträge als auch bei den Zitationen. Dies widerspricht spätestens seit der Veröffentlichung von ChatGPT Ende 2022 dem generellen Eindruck, dass die wesentlichen KI-Innovationen derzeit nicht aus China, sondern aus den USA kommen sowie der allgemeinen Einschätzung, dass auch die deutsche und europäische Forschung wichtige Beiträge zur KI-Entwicklung liefern. Ein Grund für dieses Auseinanderklaffen ist die Tatsache, dass KI ein sehr heterogenes Forschungs- und Innovationsfeld ist, das aus verschiedenen Technologien, Methoden und Anwendungen besteht. Eine einheitliche Definition gibt es bisher nicht. Für Ländervergleiche, die auf bibliometrischen Analysen und auf Patentauswertungen basieren, sind adäquate Forschungsfelddefinitionen aber essentiell.

Dieses Discussion Paper versteht sich als Beitrag zum einen zur Eingrenzung des Forschungs- und Innovationsfeldes „Künstliche Intelligenz" und zum anderen zur Frage, inwiefern man KI-Technologien als „fortgeschritten" oder „weniger fortgeschritten" klassifizieren kann. Denn die Entwicklung des Forschungsfeldes verläuft sehr dynamisch und ist von Innovationssprüngen geprägt, die sich nicht alleine über Publikations- und Patentanalysen erschließen.

Zur Beantwortung der Forschungsfragen werden zunächst acht einschlägige bibliometrische Studien sowie das derzeit bekannteste Klassifikationsschema für Machine-Learning (ML)-Systeme analysiert. Dabei werden gleichzeitig Hinweise zur Beantwortung der Frage nach den Qualitätsleveln gesammelt. Zusätzlich zur Literaturauswertung wurde die Struktur von KI-Lehrbüchern und KI-Studiengänge analysiert. Und es wurden zwischen März und September 2024 insgesamt 18 Experteninterviews mit dem Ziel geführt, ein tieferes Verständnis des Forschungsgegenstands und seiner historischen Entwicklung zu erhalten.

Im Ergebnis präsentiert diese Untersuchung eine eigene Keywordliste mit 19 Haupt- und 72 Untereinträgen, welche den aktuellen Stand des Forschungs- und Innovationsfeldes KI abbildet. Die Liste stellt eine Synthese aus den untersuchten Studien dar, denn es zeigte sich, dass keine der existierenden Listen das Forschungsfeld vollständig abdecken. Die eigene Keywordliste deckt sowohl die etablierten KI-Forschungsbereiche (symbolische KI) als auch die aktuell im Vordergrund stehenden Machine Learning-basierten Forschungsfelder (statistische KI) ab. Außerdem berücksichtig sie zentrale Anwendungsfelder der KI, wie z.B. robotics, automation, facial recognition oder machine translation, die neben der Grundlagenforschung ebenfalls für die Entwicklung von KI-Technologien von Bedeutung sind. Zur Vertiefung der Frage nach den Qualitätsleveln von KI-Technologien kann sie außerdem als Ausgangspunkt für weitere Analysen verwendet werden.

Die Recherche zeigt, dass Generative KI bzw. Large Language Models derzeit die anspruchsvollsten KI-Forschungsgebiete sind. Erforderlich sind hier neben umfangreichem Know-How enorme Rechenkapazitäten und die Verarbeitung enormer Datenmengen. Allerdings, so unser Fazit der Diskussion um Ansätze zur Bestimmung von Qualitätsleveln, sollte die aktuelle Dominanz von Sprachmodellen nicht darüber hinwegtäuschen, dass auch die älteren KI-Forschungsbereiche, die inzwischen als Good-old-fashioned AI (GOFAI) bezeichnet werden, zum Fortschritt beitragen und deshalb bei Performance-Vergleichen entsprechende Beachtung finden sollten.

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1 Research question and method

"Artificial intelligence" is a heterogeneous field of research consisting of various technologies, methods and applications. To date, there is no uniform definition for this field of research. Nevertheless, country comparisons on the performance of the respective AI research are presented regularly (see e.g. AI Index Report 2024 or OECD 2024). The country comparisons are usually based on publication data derived from keyword searches in literature databases. Or research field definitions ("subject areas" or "fields") are used, which can be selected in the respective literature databases. In many cases, it is not made transparent how the research field "artificial intelligence" is defined, which sub-areas it comprises and which it does not. Accordingly, the structure and dynamics of the research field of AI remain in the dark, and the country comparisons often contribute little to an understanding of the development of artificial intelligence beyond the ranking.

In terms of content, it is noticeable in the country comparisons that China has been in first place for years - both in terms of the number of AI research articles and of citations. Since the publication of ChatGPT at the end of 2022 at the latest, this contradicts the general impression that the main AI innovations are currently coming from the USA rather than China, as well as the general assessment that German and European research is also making important contributions to AI development (see Bitkom 2023).

It has been suggested that the reason for this contradiction is primarily a size effect, as there are many more AI researchers active in China than in other regions of the world. However, it has also been claimed that Chinese research contributions lack "real substance" and that they actually lag two to three years behind US research (see Toner, Xia, Ding 2023[1]). Others, on the other hand, do not want to write China off too early in the competition for AI leadership (e.g. Brainard; Normile 2022 or Min et al. 2023). The central question that studies such as these leave unanswered is: What *is* high-quality or advanced AI research? What characterizes it and how well do the proposed metrics cover the entire AI development process?

This working paper is intended as a contribution to the current discussion about an adequate definition of the research field of "artificial intelligence" and to the question of the extent to which AI technologies can be classified as "advanced" or "less advanced". The aims of this paper are therefore to identify and compile a keyword list that can be used as a basic definition for the research field of AI and is also suitable for further analysis, as well as to discuss approaches to defining advanced or "high-level" AI as opposed to "less advanced" or "standard AI".

To answer the two research questions, eight relevant bibliometric studies and the currently best-known classification scheme for machine learning (ML) systems are first analyzed.

The starting point for the bibliometric analysis is the frequently cited OECD expert study from 2020 entitled "Identifying and measuring developments in artificial intelligence: Making the impossible possible". At first glance, the keyword list used there with its 168 entries appears to be very broad and unspecific in parts. A step-by-step delimitation and concretization of the AI sub-areas is then attempted on the basis of the work of Liu, Shapria, and Yue 2021, Gao and Ding 2022, CSET 2023, Zeta Alpha 2023 and the Würzburg Group 2023.

The work of NLLG 2023 and Epoch AI 2024 places a special focus on machine learning models and large language models (LLMs). The OECD evaluations for the OECDS.ai web tool focus on the specific fields of application of AI (OECD.ai 2024).

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[1] Toner, Xia, Ding 2023 claim that "Chinese LLMs are at least two or three years behind their state-of-the-art counterparts in the United States (...). Worse, advances in China rely a great deal on reproducing and tweaking research published abroad".

The studies mentioned are analyzed below with a view to an "ideal" basic definition of AI, a definition that is broad enough to cover the entire field including current developments and at the same time specific enough to generate as few false hits as possible.

When analyzing the methodological and comparative studies, attention was paid to indications that could provide answers to the question of what distinguishes high-quality AI from standard AI. In addition, AI textbooks and AI degree courses were analyzed with regard to their respective structuring of the research area. And a total of 18 expert interviews were conducted between March and September 2024 (in person, by telephone or in writing by email). The aim of the interviews was to gain a deeper understanding of the research subject, the structure of the research field and the respective contexts and to obtain further information on possible distinctions between quality levels. The results of the interviews do not form a separate chapter in this paper, but are included at various points in the evaluation of the studies and when compiling our own keyword list.

The most important finding of this part of the research is that the currently most challenging area of AI research is also the area that is currently attracting the most attention from researchers and the public: The field of generative AI, or large language models. This area is particularly challenging because, in addition to extensive expertise in neural networks, it requires enormous computing capacities and the processing of huge amounts of data. However, AI research also encompasses other sub-areas, such as knowledge ontologies or rule-based decision support systems. These AI research areas, which existed before the current hype surrounding large language models, are now referred to as Good-Old-Fashioned AI (GOFAI, see e.g. Morris 2023).

In fact, the current dominance of language models should not obscure the fact that these other areas of AI research have also contributed to progress and will continue to do so in the future. Combinations with GOFAI technologies are particularly promising in research work that is currently dealing with the weaknesses of large language models, namely their unreliability and "hallucination", or in specialized applications that require fewer resources to develop. Accordingly, a consideration of relevant AI research and innovation areas should take into account new and old research areas as well as purely fundamental areas and specific applications.

2 Bibliometric definitions of AI

2.1 OECD 2020: Starting point for a basic definition of AI

The starting point for the investigation of bibliometric definitions of AI research is the much-cited OECD study from 2020 with the revealing title "Identifying and measuring developments in artificial intelligence: Making the impossible possible" (OECD 2020). According to the authors, the definition of AI research seems impossible because methods and findings from different scientific disciplines are used in this research area, because some AI technologies have developed into their own sub-areas that are highly visible in the community and others have not; because there have been repeated fundamental changes of directions and because AI technologies have also developed further within application areas, such as genetics or robotics, and can no longer be considered separated from these (OECD 2020, p. 12f).

In order to make the seemingly impossible possible, the authors of the OECD study used a text mining approach to identify similar scientific articles and contributions and describe them by using keywords. In addition to scientific publications, sources for the text mining procedure included patents and software (which were published on the Github platform, see OECD 2020, p. 12). As a result, the OECD study presents a list of 168 keywords, ranging from "action recognition" to "xgoost" (see Table 1).

Of the 168 keywords, 39 were described as "somewhat general" in a subsequent expert review process (OECD 2020, p. 67), including keywords such as "brain-computer interface", "image processing", "text mining" or "robot". And even without these somewhat general keywords - which would generate a large number of non-AI-related hits in a corresponding search - the OECD's keyword list appears to be very broad and partly unspecific.

Since the publication of the keyword list, the OECD itself has not made any attempts to create a more concise list. However, in a follow-up study on AI patents from 2023, it defined eleven generic terms for AI technologies in order to narrow down the field of research. These were published in the report "What technologies are at the core of AI? An exploration based on patent data" (OECD 2023). The eleven generic terms are as follows:

- Algorithms,
- Chatbot,
- Autonomous driving,
- Computer or image vision,
- Feature engineering,
- General AI,
- Networks (deep learning),
- Natural language processing,
- Recognition or detection,
- Robotics and
- Speech (see Table 2).

Table 1: The OECD 2020 keyword list

Annex Table C.1. List of AI-related keywords

action recognition human action recognition	activity recognition human activity recognition	adaboost
adaptive boosting	adversarial network generative adversarial network	*ambient intelligence*
ant colony ant colony optimisation	artificial intelligence human aware artificial intelligence	association rule
autoencoder	*autonomic computing*	*autonomous vehicle*
autonomous weapon	backpropagation	Bayesian learning
bayesian network	bee colony artificial bee colony algorithm	blind signal separation
bootstrap aggregation	*brain computer interface*	brownboost
chatbot	classification tree	cluster analysis
cognitive automation	cognitive computing	*cognitive insight system*
cognitive modelling	collaborative filtering	collision avoidance
community detection	computational intelligence	*computational pathology*
computer vision	*cyber physical system*	*data mining*
decision tree	deep belief network	deep learning
dictionary learning	dimensionality reduction	*dynamic time warping*
emotion recognition	ensemble learning	evolutionary algorithm differential evolution algorithm multi-objective evolutionary algorithm
evolutionary computation	face recognition	facial expression recognition
factorisation machine	feature engineering	feature extraction
feature learning	feature selection	*firefly algorithm*
fuzzy c fuzzy environment fuzzy logic fuzzy number fuzzy set intuitionistic fuzzy set fuzzy system *t s fuzzy system* *Takagi-Sugeno fuzzy systems*	gaussian mixture model	gaussian process
genetic algorithm	genetic programming	gesture recognition
gradient boosting gradient tree boosting	graphical model	*gravitational search algorithm*
hebbian learning	hierarchical clustering	high-dimensional data high-dimensional feature high-dimensional input high-dimensional model high-dimensional space high-dimensional system
image classification	*image processing*	image recognition
image retrieval	*image segmentation*	independent component analysis
inductive monitoring	instance-based learning	*intelligence augmentation*
intelligent agent intelligent software agent	intelligent classifier	intelligent geometric computing
intelligent infrastructure	Kernel learning	K-means
latent dirichlet allocation	latent semantic analysis	latent variable

layered control system	learning automata	link prediction
logitboost	long short term memory (LSTM)	lpboost
machine intelligence	machine learning extreme machine learning	machine translation
machine vision	madaboost	MapReduce
Markovian hidden Markov model	memetic algorithm	meta learning
motion planning	multi task learning	multi-agent system
multi-label classification	multi-layer perceptron	multinomial naïve Bayes
multi-objective optimisation	naïve Bayes classifier	natural gradient
natural language generation	natural language processing	natural language understanding
nearest neighbour algorithm	neural network artificial neural network convolutional neural network deep convolutional neural network deep neural network recurrent neural network	neural turing neural turing machine
neuromorphic computing	*non negative matrix factorisation*	object detection
object recognition	*obstacle avoidance*	pattern recognition
pedestrian detection	policy gradient methods	Q-learning
random field	random forest	rankboost
recommender system	regression tree	reinforcement learning
relational learning statistical relational learning	*robot* *biped robot* *humanoid robot* *human-robot interaction* *industrial robot* *legged robot* *quadruped robot* *service robot* *social robot* *wheeled mobile robot*	*rough set*
rule learning rule-based learning	self-organising map	self-organising structure
semantic web	semi-supervised learning	*sensor fusion* *sensor data fusion* *multi-sensor fusion*
sentiment analysis	similarity learning	simultaneous localisation mapping
single-linkage clustering	sparse representation	spectral clustering
speech recognition	speech to text	stacked generalisation
stochastic gradient	supervised learning	support vector regression
swarm intelligence	swarm optimisation particle swarm optimisation	temporal difference learning
text mining	text to speech	topic model
totalboost	trajectory planning	trajectory tracking
transfer learning	trust region policy optimisation	*unmanned aerial vehicle*
unsupervised learning	variational inference	vector machine support vector machine
virtual assistant	*visual servoing*	xgboost

Source: OECD 2020, p. 66f.

The 168 keywords from the 2020 list were assigned to the above listed eleven generic terms, so that the 2023 definition does not differ from the 2020 definition at the level of individual technologies. However, the introduction of eleven topic clusters represents a conceptually interesting focus. According to the OECD, clustering is based on an iterative process in which results from word pair analyses were evaluated by experts (OECD 2023, p. 19f). According to the OECD, the eleven AI topic clusters identified in this way are the "AI main topics" (see Table 2).

Table 2: AI definition and clusters according to the OECD 2023 patent analysis

Table A A.1. List of AI keywords and corresponding AI topics

Algorithms	adaboost adaptive boosting ant colony ant colony optimisation artificial bee colony algorithm association rule backpropagation bayesian learning bayesian network bootstrap aggregation classification tree decision tree dictionary learning differential evolution algorithm dynamic time warping evolutionary algorithm evolutionary computation extreme learning machine fuzzy c fuzzy logic fuzzy number	fuzzy set gaussian mixture model gaussian process genetic algorithm genetic programming gradient boosting gradient tree boosting graphical model hebbian learning hidden Markov model hierarchical clustering k-means logitboost markovian memetic algorithm multi-objective evolutionary algorithm naive Bayes classifier natural gradient nearest neighbour algorithm particle swarm optimisation	q-learning random field random forest rankboost regression tree rough set rule learning self-organising map spectral clustering stacked generalization statistical relational learning stochastic gradient support vector machine support vector regression swarm optimisation temporal difference learning variational inference vector machine xgboost
Chatbot	chatbot	virtual assistant	
Autonomous driving	autonomous vehicle blind signal separation	collision avoidance motion planning	unmanned aerial vehicle pedestrian detection
Computer or image vision	computer vision face recognition image classification image processing	image recognition image retrieval image segmentation machine vision	obstacle avoidance visual servoing
Feature engineering	data mining dimensionality reduction factorisation machine feature engineering feature extraction feature learning	feature selection high-dimensional data high-dimensional feature high-dimensional input high-dimensional space independent component analysis	mapreduce non negative matrix factorisation simultaneous localisation mapping sparse representation
General AI	ambient intelligence artificial intelligence autonomic computing brain computer interface cluster analysis cognitive automation cognitive computing cognitive modelling collaborative filtering computational intelligence cyber physical system ensemble learning inductive monitoring	instance-based learning intelligence augmentation intelligent agent intelligent classifier intelligent infrastructure intelligent software agent Kernel learning learning automata machine intelligence machine learning meta learning multi task learning multi-agent system	multi-label classification multi-objective optimisation neuromorphic computing recommender system reinforcement learning relational learning rule-based learning semi-supervised learning similarity learning supervised learning swarm intelligence transfer learning unsupervised learning
Networks (deep learning)	adversarial network artificial neural network convolutional neural network deep belief network deep convolutional neural network	deep learning deep neural network generative adversarial network long short term memory (LSTM)	multi-layer perceptron neural network neural turing recurrent neural network

Natural language processing	autoencoder latent dirichlet allocation latent semantic analysis latent variable	machine translation natural language generation natural language processing natural language understanding	semantic web sentiment analysis text mining topic model
Recognition or detection	action recognition activity recognition community detection emotion recognition facial expression recognition	gesture recognition human activity recognition human action recognition link prediction object detection	object recognition pattern recognition trajectory planning trajectory tracking
Robotics	biped robot humanoid robot human-robot interaction industrial robot	legged robot multi-sensor fusion robot sensor data fusion	sensor fusion service robot social robot
Speech	speech recognition	speech to text	text to speech

Source: OECD 2023, p. 42f

Although patent data was only available up to 2018, the cluster list includes topics such as "chatbot", "natural language processing" and "speech", i.e. topics that have only subsequently attracted greater attention in the scientific community and, since the publication of ChatGPT at the end of 2022, in the wider public. On the other hand, the list lacks keywords that could address current developments more specifically, such as "large language models", "generative AI" or "transformer".

The OECD has become an important point of contact for AI analyses and AI country comparisons in the areas of regulation, governance analysis and trustworthy AI. A large number of studies and policy papers have been published in recent years (see www.oecd.org/en/topics/policy-issues/artificial-intelligence.html). Since the beginning of 2024, a web tool called "Live data" has been available at the web address https://oecd.ai/en, which enables country comparisons of scientific performance in selected AI research fields. The evaluations are based on data from Scopus and OpenAlex. This web tool is discussed in more detail in section 2.8.

However, following the fundamental 2020 study and the 2023 study, which focused on patent analyses, the OECD did not undertake any further bibliometric work of its own to define AI. In March 2024, it did publish an "Explanatory Memorandum on the updated OECD definiton of an AI system" (OECD 2024a) entitled "Update". However, this "update" does not refer to the definition of AI research fields, but to another strand of the OECD's involvement with AI, which is concerned with the verbal definition of AI and its functions and applications. A verbal description of what AI systems are and what they can do is a precondition for an governing and regulating the technology and its applications. Accordingly, the 2024 update does not refer to the 2020 methodological report, but to the 2019 OECD Guidelines for Trustworthy AI (OECD 2019).

In the 2024 update of these guidelines, the OECD took into account the fact that AI systems can continue to develop even after their implementation, which has corresponding implications for regulation (see also OECD 2022). In addition, the updated definition should reflect that AI systems can also produce text, speech or images (i.e. "content"), an aspect that was missing in the 2019 definition.

The updated verbal definition of AI is:

> *"An AI system is a machine-based system that, for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations, or decisions that can influence physical or virtual environments. Different AI systems vary in their levels of autonomy and adaptiveness after deployment." (OECD 2024a, p. 4).*

The distinction between autonomy and adaptivity introduced here seems particularly interesting for the more precise definition of AI technologies. This is because AI systems with a high degree of autonomy and adaptivity differ from simple AI systems or from non-AI systems that work with fixed rules. The extent to which such conceptual distinctions are helpful in guiding bibliometric studies on AI research will not be discussed in depth here. However, it is clear that AI systems can have different levels of quality resulting from the interaction of specific AI technologies.

For a more precise definition of the AI research field, further bibliometric studies are consulted below, which were carried out after the 2020 OECD study.

2.2 Liu, Shapira and Yue 2021: Three keyword lists for the definition of AI

The first study was conducted by Liu, Shapira and Yue and was published in Scientometrics in 2021 under the title "Tracking developments in artificial intelligence research: Constructing and applying a new search strategy". The methods section comprises just under 20 pages, the analysis section (country comparison of output and citations, top institutions, collaboration patterns, funding sponsors, scientific disciplines involved) 11 pages.

In order to characterize the research field of AI, a multi-stage procedure was used, which mainly aims at completeness, i.e. with aims to identiy all AI research areas, even those that don't look like it at first glance (Liu, Shapira and Yue 2021, p. 3156f). The starting point for the research was scientific articles from eight Web of Science (WoS) subject categories and from 19 high-ranking scientific journals. From the more than 40,000 documents (published between 2010 and 2020), "author keywords" and "keywords plus" were then extracted and displayed according to frequency. The result is a list of 204 keyword candidates, which was further specified. For this purpose, all 204 high-frequency terms were combined with all ten keywords from the previously obtained "core lexical list" (co-occurance analysis). The ten "core lexical keywords" are:

- Artifcial Intelligen*,
- Neural Net*,
- Machine* Learning,
- Expert System$,
- Natural Language Processing,
- Deep Learning,
- Reinforcement Learning,
- Learning Algorithm$,
- Supervised Learning,
- IntelligentAgent* (Liu, Shapira and Yue 2021, p. 3160).

The co-occurance analysis resulted in a so-called hit ratio, i.e. a percentage value that indicated how many of the terms from the core lexical list were found in the corresponding article or in the extended publication pool. A threshold value was then defined, above which a specific keyword from the list of the 204 candidates should be included in the final keyword list: From a threshold value of 70% the keyword was directly included in the final list (result: 28 keywords, see Table 3), at a threshold value between 30% and 70% a manual review decided on the inclusion (result: 62 keywords included, see Table 4).

Table 3: The 28 AI keywords from the expanded definition by Liu, Shapira and Yue 2021

Table 2 Candidate keywords directly included in the search strategy

Number	Keywords	Candidate terms	B	$A \cap B$	Hit ratio (%)	Final decision
1	Backpropagation Learning	"Backpropagation Learning" or "Back-propagation Learning" or "Bp Learning"	381	373	97.9	Include
2	Backpropagation Algorithm	"Backpropagation Algorithm*" or "Back-propagation Algorithm*"	1348	1252	92.9	Include
3	Long Short-term Memory	"Long Short-term Memory"	2316	2111	91.2	Include
4	Pcnn	(Pcnn$ not Pcnnt) or "Pulse Coupled Neural Net*"	321	286	89.1	Include
5	Perceptron	"Perceptron$"	5836	5042	86.4	Include
6	Neuro Evolution	"Neuro-evolution" or Neuroevolution	132	114	86.4	Include
7	Liquid State Machine	"Liquid State Machine*"	47	40	85.1	Include
8	Deep Belief Net	"Deep Belief Net*"	861	723	84.0	Include
9	Radial Basis Function Network	"Radial Basis Function Net*" or Rbfnn* or "Rbf Net*"	1985	1654	83.3	Include
10	Deep Network	"Deep Net*"	1119	930	83.1	Include
11	Autoencoder	Autoencoder*	1996	1644	82.4	Include
12	Committee Machine	"Committee Machine*"	140	115	82.1	Include
13	Training Algorithm	"Training Algorithm$"	1533	1252	81.7	Include
14	Backpropagation Network	"Backpropagation Net*" or "Back-propagation Net*" or "Bp Network*"	566	456	80.6	Include
15	Q learning	"Q learning"	1218	980	80.5	Include
16	Convolutional Network	"Convolution* Net*"	1796	1443	80.4	Include
17	Actor-critic Algorithm	"Actor-critic Algorithm$"	69	55	79.7	Include
18	Feedforward Network	"Feedforward Net*" or "Feed-Forward Net*"	1168	929	79.5	Include
19	Hopfield Network	"Hopfield Net*"	198	157	79.3	Include
20	Neocognitron	Neocognitron*	46	36	78.3	Include
21	Xgboost	Xgboost*	372	288	77.4	Include
22	Boltzmann Machine	"Boltzmann Machine*"	849	655	77.2	Include
23	Activation Function	"Activation Function$"	2337	1800	77.0	Include
24	Neurodynamic Programming	"Neurodynamic Programming" or "Neuro dynamic Programming"	40	30	75.0	Include
25	Learning Model	"Learning Model*"	8007	5790	72.3	Include

Source: Liu, Shapira and Yue 2021, p. 3161f (list of 28 with a hit ratio between 100 and 70%, all "included")

Table 4: The 62 additional AI keywords ("Include") of the definition by Liu, Shapira and Yue 2021

Table 3 Candidate keywords subject to manual review

Number	Keywords	Candidate terms	B	$A \cap B$	Hit ratio (%)	N	Noise Ratio	Final decision
1	Transfer Learning	"Transfer Learning"	2269	1588	70.0	21	LR	Include
2	Gradient Boosting	"Gradient Boosting"	1152	804	69.8	25	LR	Include
3	Adversarial Learning	"Adversarial Learning"	187	129	69.0	25	LR	Include
4	Feature Learning	"Feature Learning"	1574	1085	68.9	25	LR	Include
5	Heuristic Dynamic Programming	"Heuristic Dynamic Programming"	99	68	68.7	5	HR	Exclude
6	Generative Adversarial Network	"Generative Adversarial Net*"	1080	738	68.3	23	LR	Include
7	Representation Learning	"Representation Learning"	793	532	67.1	24	LR	Include
8	Multiagent Learning	"Multiagent Learning" or "Multi-agent Learning"	106	71	67.0	25	LR	Include
9	Reservoir Computing	"Reservoir Computing"	361	238	65.9	18	LR	Include
10	Co-training	"Co-training"	182	114	62.6	24	LR	Include
11	Pac Learning	"Pac Learning" or "Probabl* Approximate* Correct Learning"	64	40	62.5	25	LR	Include
12	Extreme Learning Machine	"Extreme Learning Machine*"	3842	2394	62.3	24	LR	Include
13	Instance-based Learning	"Instance-based Learning"	152	89	58.6	10	HR	Exclude
14	Recurrent Network	"Recurrent* Net*"	712	416	58.4	4	HR	Exclude
15	Competitive Learning	"Competitive Learning"	245	134	57.5	11	HR	Exclude
16	Ensemble Learning	"Ensemble Learning"	1935	1110	57.4	25	LR	Include
17	Learning Rule	"Learning Rule*"	1132	639	56.5	9	HR	Exclude
18	Propagation Algorithm	"Propagation Algorithm$"	1637	920	56.2	5	HR	Exclude
19	Machine Intelligence	"Machine* Intelligen*"	291	162	55.7	24	LR	Include
20	Neuro fuzzy	"Neuro fuzzy" or Neurofuzzy	4324	2379	55.0	25	LR	Include
21	Stochastic gradient descent	"Stochastic gradient descent"	321	585	54.9	11	HR	Exclude
22	Lazy Learning	"Lazy Learning"	64	35	54.7	25	LR	Include
23	Multiple-instance Learning	"Multi* instance Learning" or "Multiinstance Learning"	395	213	53.9	25	LR	Include
24	Multi-task Learning	"Multi* task Learning" or "Multitask Learning"	928	500	53.9	25	LR	Include
25	Computational Intelligence	"Computation* Intelligen*"	1511	813	53.8	25	LR	Include
26	Neural Model	"Neural Model*"	1411	756	53.6	25	LR	Include

Table 3 (continued)

Number	Keywords	Candidate terms	*B*	*A*∩*B*	Hit ratio (%)	N	Noise Ratio	Final decision
27	Multi Label Learning	"Multi* Label Learning" or "Multilabel Learning"	420	225	53.6	25	LR	Include
28	Similarity Learning	"Similarity Learning"	152	78	51.3	25	LR	Include
29	Statistical Relational Learning	"Statistical Relation* Learning"	80	41	51.3	25	LR	Exclude
30	Support Vector Regression	"Support* Vector* Regression"	4655	2359	50.7	25	LR	Include
31	Manifold Regularization	"Manifold Regulari?ation"	310	157	50.7	25	LR	Include
32	Decision Forest	"Decision Forest*"	191	96	50.3	24	LR	Include
33	Generalization Error	"Generali?ation Error*"	469	232	49.5	24	LR	Include
34	Adaptive Dynamic Programming	"Adaptive Dynamic Programming" or "Approximat* Dynamic Programming"	926	457	49.4	5	HR	Exclude
35	Transductive Learning	"Transductive Learning"	122	60	49.2	25	LR	Include
36	Neurorobotics	Neurorobotic* or "Neuro-robotic*"	110	54	49.1	25	LR	Include
37	Inductive Logic Programming	"Inductive Logic Programming"	122	59	48.4	25	LR	Include
38	Natural Language Understanding	"Natural Language Understanding"	120	57	47.5	24	LR	Include
39	Adaboost	Adaboost* or "Adaptive Boosting"	1707	801	46.9	23	LR	Include
40	Incremental Learning	"Incremental Learning"	967	452	46.7	16	LR	Include
41	Random Forest	"Random Forest*"	14,190	6594	46.5	23	LR	Include
42	Cognitive Computing	"Cognitive Computing"	190	88	46.3	7	HR	Exclude
43	Metric Learning	"Metric Learning"	890	407	45.7	25	LR	Include
44	Neural Gas	"Neural Gas"	165	75	45.5	24	LR	Include
45	Grammatical Inference	"Grammatical Inference"	62	28	45.2	25	LR	Include
46	Support Vector Machine	"Support* Vector* Machine*"	34,278	15,250	44.5	20	LR	Include
47	Multi Label Classification	"Multi* Label Classification" or "Multilabel Classification"	668	297	44.5	18	LR	Include
48	Chatbot	Chatbot*	153	67	43.8	8	HR	Exclude
49	Conditional Random Field	"Conditional Random Field*"	1296	562	43.4	19	LR	Include
50	Intelligent System	"Intelligent System*"	2365	1018	43.0	11	HR	Exclude
51	Multi Class Classification	"Multi* Class Classification" or "Multiclass Classification"	1262	542	43.0	17	LR	Include

Table 3 (continued)

Number	Keywords	Candidate terms	*B*	*A*∩*B*	Hit ratio (%)	N	Noise Ratio	Final decision
52	Mixture Of Experts	"Mixture Of Expert*"	173	74	42.8	23	LR	Include
53	Concept Drift	"Concept* Drift"	447	191	42.7	25	LR	Include
54	Genetic Programming	"Genetic Programming"	2267	957	42.2	18	LR	Include
55	String Kernel	"String Kernel*"	88	37	42.1	14	LR	Include
56	Learning To Rank	"Learning To Rank*" or "Machine-learned ranking"	395	164	41.5	25	LR	Include
57	Boosting Algorithm	"Boosting Algorithm$"	436	181	41.5	25	LR	Include
58	Robot Learning	"Robot* Learning"	200	83	41.5	21	LR	Include
59	Relevance Vector Machine	"Relevance Vector* Machine*"	550	228	41.5	25	LR	Include
60	Feature Selection	"Feature Selection"	14,472	5833	40.3	12	HR	Exclude
61	Computational Learning	"Computational Learning"	133	53	39.9	9	HR	Exclude
62	Adaptive Learning	"Adaptive Learning"	1514	602	39.8	12	HR	Exclude
63	Gradient Descent	"Gradient Descent"	3454	1327	38.4	7	HR	Exclude
64	Pattern Classification	"Pattern Classification"	2497	952	38.1	11	HR	Exclude
65	Connectionism	Connectionis*	139	53	38.1	20	LR	Include
66	Multiple Kernel Learning	"Multi* Kernel$ Learning" or "Multikernel$ Learning"	694	259	37.3	25	LR	Include
67	Graph Learning	"Graph Learning"	172	64	37.2	17	LR	Include
68	Naive Bayes Classifier	"Naive Bayes* Classifi*"	1119	412	36.8	14	LR	Include
69	Rule-based System	"Rule-based System$"	768	274	35.7	21	LR	Include
70	Classification Algorithm	"Classification Algorithm*"	5510	1960	35.6	15	LR	Include
71	Graph Kernel	"Graph* Kernel*"	198	69	34.9	21	LR	Include
72	Rule Induction	"Rule* Induction"	316	110	34.8	22	LR	Include
73	Feature Extraction	"Feature Extraction"	18,493	6368	34.4	12	HR	Exclude
74	Decision Tree	"Decision Tree*"	11,257	3848	34.2	11	HR	Exclude
75	Generative Model	"Generative Model*"	1702	569	33.4	10	HR	Exclude
76	Intelligent Control	"Intelligent Control*"	1465	487	33.2	7	HR	Exclude

Table 3 (continued)

Number	Keywords	Candidate terms	*B*	*A*∩*B*	Hit ratio (%)	N	Noise Ratio	Final decision
77	Manifold Learning	"Manifold Learning"	1331	442	33.2	21	LR	Include
78	Structured Learning	"Structur* Learning"	1059	351	33.1	9	HR	Exclude
79	Label Propagation	"Label Propagation"	541	178	32.9	25	LR	Include
80	Hypergraph Learning	"Hypergraph* Learning"	67	22	32.8	25	LR	Include
81	Case-based Reasoning	"Case-based Reasoning"	1007	327	32.5	8	HR	Exclude
82	One Class Classifiers	"One Class Classifi*"	482	156	32.4	24	LR	Include
83	Intelligent Algorithm	"Intelligent Algorithm*"	884	285	32.2	25	LR	Include
84	Bio Inspired Computing	"Bio* Inspired Computing" or "Bioinspired Computing"	200	61	30.5	12	HR	Exclude

Analysis of articles in SCI-E and SSCI in WoS core collection (2010-March 2020). Document type: article. Language: English. *N* represents the number of records out of a 25-record random sample falling in the area of (*B* not *A*∩*B*) relevant artificial intelligence records. HR represents "High noise ratio", with less than 50% of the 25-record random sample falling in the area of (*B* not *A*∩*B*) relevant artificial intelligence records. LR represents "Low noise ratio", with more than 50% of the 25-record random sample falling in the area of (*B* not *A*∩*B*) relevant artificial intelligence records

Source: Liu, Shapira and Yue 2021, p. p. 3163-66 (list of 62 with a hit ratio between 70% and 30%, only keywords marked with "Include" were counted)

The results of this extensive research were therefore three keyword lists, the core lexical keywords (10 entries, see list above), the keywords taken directly from the co-occurance check (28 entries, see Table 3) and the additional 62 keywords with lower co-occurance values after manual checking (see Table 4).

The broad, multi-level approach suggests that these three lists comprehensively represent the AI research field (at the time of the survey). For example, care was also taken to ensure that Chinese reference sources were taken into account when selecting the overall corpus (p. 3158). At the same time, the keyword set of Liu, Shapira and Yue appears more precise than that of the OECD of 2020, not only because it uses fewer terms overall, but also because it contains fewer terms that could overlap with non-AI research areas.

However, some terms that had a major impact on the AI debate in 2024 did not make it onto Liu, Shapira and Yue's list. They were either excluded because there were too few articles on these topics at the time of the survey or because they did not yet form their own research areas. Examples of keywords that are relevant in 2024 but were excluded by Liu, Shapira and Yue in 2021 because they did not meet the threshold are: "computer vision", "natural language generation", "generative model" or "chatbots". Examples of terms that were not yet research areas in their own right at the time of the survey and therefore could not appear as keyword candidates are: "large language models", "transformer" or "generative AI".

Furthermore, there is no evaluation of the development of the strength of the research fields over time. The authors fail to answer the obvious question of how the individual, elaborately identified research areas have developed over the 10 years under review, which sub-areas have become stronger and which weaker.

2.3 Gao and Ding 2022: Basic definition and top increaser

One study that set out to do exactly this, namely to determine the dynamics in the field of AI research, is the study by Gao and Ding, which was published in the journal "Multimedia Tools and Applications" in 2022 under the title "The research landscape on the artificial intelligence: A bibliometric analysis of recent 20 years".

As in the OECD study 2020 and in Liu, Shapira and Yue 2021, a multi-stage keyword analysis process is used to first try to define the research field of artificial intelligence comprehensively and specifically at the same time. The starting point is again scientific articles from the Scopus database; the first selection round is based on the three keywords "artificial intelligence", "machine intelligence" and "machine learning". Articles submitted to 15 different renowned AI conferences were also analyzed. In addition, Gao and Ding consider patent data from the Derwent Innovation Index (DII) (Gao; Ding 2022, p. 12975f).

As a result of their multi-stage extraction process, Gao and Ding present a keyword list that characterizes AI research in the years between 2015 and 2019. The list consists of 20 entries:

- Machine Learning,
- Learning algorithm,
- Artificial intelligence,
- Support vector machine,
- Classification,
- Neural network,
- Artificial neural network,
- Prediciton,
- Random forest,
- Feature selection,
- Deep learning,
- Data mining,
- Deep neural network,
- Supervised learning,
- Computer vision,
- Reinforcement learning,
- Big data,
- Generic algorithm,
- Decision tree,
- Natural language processing (Gao; Ding 2022, Table 6, p. 12990, 2015-2019).

In principle, this list could also be used as a basic definition for AI, although it is noticeable that it has fewer entries and is also less specific than the keyword set from Liu, Shapira and Yue 2021 presented above. Entries such as "classification", "prediction", "data mining" or "big data" also appear as entries that are also relevant outside the AI research field and could therefore result in many non-AI hits in a separate evaluation.

The comparison of the lists also shows that the keyword lists can generally turn out differently, even though the chosen approach is similar. Slight variations in the type of restriction or in the setting of threshold values for cluster creation can lead to very different results.

Following the compilation of the keyword list, Gao and Ding examine the question of which AI research fields contain the most publications, i.e. the question of which research topics the AI community has focused on in different time periods.[2]

For that matter they carry out a co-citation analysis of the 200 most-cited AI articles. The resulting co-citation clusters show the AI subdomains in which research activities are concentrated. According to Gao and Ding, these are the following four areas for the period 2010 to 2019:

- Random forest (Numerical computation classification, distribution, prediction, regularization, regression tree),
- Deep learning (neural network, dimension reduction, tree search, visual/speech recognition),
- Evolving fuzzy grammar (image features, face detection, pattern recognition, natural language processing, transfer learning, text expression),

[2] Although Liu, Shapira and Yue 2021 did not explicitly pursue this question, but their tables show that the top 4 topics are "Support Vector machine", "Random Forest", "Learning Model" and "Perception" (column "B" in table 2 and 3 in Liu, Shapria, Yue 2021).

- Machine learning (comparison, data clustering, data mining, representation learning, text categorization) (see Table 5 in Gao and Ding 2022, p. 12984f, the terms in brackets are called "topics" by the authors).[3]

Gao and Ding do not limit themselves to simply listing relevant keywords, but also attempt to trace a development over the last years. To this end, they present a list of AI research fields that they refer to as "top increasers". These are topics that have recently been discussed more frequently in scientific journal articles ("journals"), but especially at scientific conferences ("conferences"), than in previous periods. Their survey covers the years 2015 to 2019.

Conference papers are regarded as an early indicator for the development of a research field in the technical disciplines and especially in the field of computer science, because articles can be published more easily and quickly. It can therefore be expected that these topics will also be dealt with in the journals with a time delay.

Gao and Ding identify the following 21 AI fields, which they refer to as "top increasers", as the main or future topics of AI for the period between 2015 and 2019:

- Supervised Learning,
- Transfer Learning,
- Mobile Robot,
- Human-agent interaction,
- Humanoid Robot,
- 3D Architecture
- Image Segmentation
- Action Recognition
- Machine Translation,
- Smart Grid
- Convolutional Neural Network CNN,
- Deep Learning,
- Deep Neural Network,
- Generative Adversarial Network GAN,
- Recurrent Neural Network RNN
- Robotics
- Image Processing
- Training Data
- Computational Intelligence
- Object detection
- Pattern recognition (Gao; Ding 2022: list of "burst terms" on p. 12992 plus "top increaser" 2015-2019 read from fig 7 on p. 12994).

Gao and Ding's basic definition with the 20 keywords and the 21 "Top Increasers" could also be used for your own research; Gao and Ding proceed with great methodological care and document their sub-steps in detail, so that it becomes clear how they arrived at which results. However, the limitations and boundaries of their analyses also become apparent.

The most obvious limitation is the fact that Gao and Ding´s list differ greatly from the other lists presented here. Although there are overlaps for top terms such as "artificial intelligence", "machine learning", "deep learning" or "neural network", the collections of terms vary greatly as a whole.

3 The difference to the ranking of Liu, Shapira and Yue 2021 is obvious, there is only one overlap with "Random forest", all other terms are different.

Another limitation is of a temporal nature, because the analysis of publication data is by nature past-oriented and therefore the current edge of AI development is disregarded. In the OECD study from 2020, as well as in Liu, Shapira and Yue from 2021 and again in Gao and Ding 2022, some of the AI topics that appear to be particularly relevant in 2024 did not make it into the keyword lists. For Gao and Ding, these are: multi-agent systems, natural language processing, computer vision, face recognition, image analysis, image classification and sentiment analysis. According to Gao and Ding, although there has been increased activity in these AI research fields in recent years ("keywords with strong bursts"), these terms did not make it above the set threshold in the co-occurance analysis ("[did] not reach the threshold", Gao; Ding 2022, p. 12987).

2.4 CSET 2023: Most elaborated basic definition of AI

Probably the most elaborate basic definition of AI comes from the US Center for Security and Emerging Technology (CSET) and was published in July 2023 under the title "Identifying AI Research" (CSET 2023). According to Wikipedia, CSET is a "think tank dedicated to policy analysis at the intersection of national and international security and emerging technologies, based at Georgetown University's School of Foreign Service" (Wikipedia "Center for Security and Emerging Technology"). CSET focuses on technologies that are of strategic importance to the USA or that have important security policy implications. Analyzing the performance of AI research and AI innovations in international competition is a central topic of the CSET departments "Compete" and "Assessment", in which, according to the CSET website, eight scientists are active. They are supported by a "data team” consisting of 15 scientists (see https://cset.georgetown.edu/research-topic).

The CSET analyses are a central source for the annual AI Index Report which has been published annually since 2017 by the University of Stanford (AI Index Report 2023). As this report is now regarded as the standard work for country comparisons in the field of AI and is therefore often cited, the analysis of the CSET methodology is particularly interesting.

The 2023 CSET paper is a methods paper in which four different AI classification options are compared with each other. The aim of the comparison is to find out which classifications best describe the AI research field, i.e. which search strategies can be used to find the most relevant publications.

The classification options investigated are as follows:

- a keyword-based search based on the keyword list that CSET compiled manually in 2020 and which contains a total of 104 English entries (Approach 1),
- a "Fields of Study"-based search, which is based on the 19 top-level and 34 subfield categories of the "Microsoft Academic Graph" (MAG) platform, which existed until 2021 (Approach 2),
- an "ArXiv Classifier"-based search based on the six ArXiv categories "artificial intelligence", "computation and language", "computer vision", "machine learning", "multiagent systems" and "robotics" (Approach 3),
- a "Map of Science Research Clusters"-based search in which the 120,000 research clusters of the Emerging Technologies Observatories (ETO) were used for mapping AI research (Approach 4).

All four search strategies were applied to the so-called "CSET Merged Corpus" - partly with the help of an AI tool that was trained for the automatic assignment of unclassified articles. The "CSET Merged Corpus" is an internal database in which more than 70 million AI-relevant publications have been recorded since 2010. According to CSET 2023, the CSET Merged Corpus consists of "journal articles, conference proceedings, dissertations, thesis papers, books, and other scientific documents" (p. 34). This means that all publications listed on the ArXiv platform and all publications from relevant AI conferences are included in the CSET Merged Corpus and can be searched there.[4]

The first step focused on the number of relevant hits: The results show that the fields-of-study and ArXiv classifier search strategies generate the most hits (2.7 million each). The keyword-based search identified 2.5 million relevant articles. The Map of Science search strategy produced only 1.7 million hits (see Table 5).

Table 5: AI publications in the CSET Merged Corpus by search strategy

	Approach 1: Keyword Search	Approach 2: Fields of Study	Approach 3: arXiv Classifier	Approach 4: Map of Science*
AI/ML Publication Count	2,489,773	2,719,355	2,711,210	1,733,379
AI/ML Publication Languages†				
English	96%	95%	100%	95%
Chinese	26%	21%	19%	16%
AI/ML Author Affiliation Available‡	78%	80%	83%	79%
United States	13%	13%	14%	13%
China	44%	41%	38%	35%
EU-27	14%	14%	16%	15%
Country Unknown	18%	20%	18%	22%

Source: CSET 2023, Table 3, p. 10

Further comparisons were made with regard to the availability of country information, research institutions and languages (English, Chinese, other languages). The different strategies show various advantages and disadvantages. The authors conclude that different search strategies should be used depending on the research question: "the divergence in results from these four methods (...) indicates that analytic results will often be sensitive to the choice of method for identifying AI/ML - relevant publications" (CSET 2023, p. 14).

In the second step, the comparison of the search strategies focused on the overlap of the hit lists. It turned out that the ArXiv classifier is best suited to finding articles published by the relevant AI conference platforms (81%). The keyword search performs rather poorly in this comparison with only 50% of articles found. This means that ArXiv and AI conference platforms only represent a section of AI research and are not representative of the entire AI research landscape (CSET 2023, p. 5 and 14). The aforementioned repositories are increasingly dealing with emerging AI research topics for which there may not yet be any equivalents in existing keyword lists or subfield categories.

As a result, the CSET keyword list seems best suited to structuring the AI research space, firstly because it contains the categories of other search strategies and secondly because it was created on the basis of an extremely extensive overall corpus. According to CSET 2023, the keyword list was compiled manually ("manual curation", p. 6) and is continuously supplemented and edited. [5] It forms the basis

[4] A more detailed description of the Merged Corpus can be found at https://eto.tech/dataset-docs/mac/#identifying-subjects. The corpus is apparently updated on a weekly basis.

[5] A manual comparison of the CSET keyword lists from 2022 (CSET 2022, Appendix D) and 2023 (CSET 2023, Appendix C) revealed eight additional entries and five deletions in the more recent version.

for many evaluations and, according to CSET, represents a "straightforward solution" that is easy to implement (CSET 2023, p. 6). The list consists of a total of 104 English keywords (see Table 6).

Table 6: CSET 2023 keyword list (104 entries)

- active learning	- incremental clustering
- adaptive learning	- information extraction
- anomaly detection	- information fusion
- artificial intelligence	- information retrieval
- artificial neural network	- k-nearest neighbor
- associative learning	- knowledge-based system*
- autoencoder	- knowledge discovery
- autonomous navigation	- knowledge representation
- autonomous system*	- language identification
- autonomous vehicle*	- machine learning
- average link clustering	- machine perception
- back propagation/ Backpropagation	- machine translation
- binary classification	- multi-class classification
- bioNLP	- multi-label classification
- boltzmann machine	- multitask learning
- character recognition	- natural language generation
- classification algorithm	- natural language processing
- classification label*	- natural language understanding
- clustering method*	- neural network
- complete link clustering	- object recognition
- computer aided diagnosis	- one-shot learning
- computer vision	- pattern matching
- convolutional neural network	- pattern recognition
- deep learning	- random forest
- ensemble learning	- recommend* system*
- evolutionary algorithm	- recurrent network
- fac* expression recognition	- recurrent neural network
- fac*identification	- reinforcement learning
- fac* recognition	- restricted Boltzmann machine
- feature extraction	- scene* classification
- feature learning	- scene* understanding
- feature matching	- self-driving car*
- feature selection	- semi-supervised learning
- feature vector	- sentiment classification
- feedforward network	- single link clustering
- feedforward neural network	- spatial learning
- fuzzy clustering	- speech processing
- generative adversarial network	- speech recognition
- gradient algorithm	- speech synthesis

- graph matching - graphical model - handwriting recognition - hierarchical clustering - hierarchical model - human robot - image annotation - image classification - image matching - image processing - image registration - image representation - image retrieval	- statistical learning - strong artificial learning - supervised learning - support vector machine - text mining - text processing - transfer learning - translation system - unsupervised learning - video classification - video processing - weak artificial interlligence - zero shot learning

Source: CSET 2023, Appendix C

However, a closer look at CSET's keyword list also reveals that the latest AI keywords such as "transformer", "chatbots" and "large language models" are missing, i.e. terms that have had a major impact on AI development since 2022. The CSET experts themselves address the need for regular updates in the 2023 study: "...developing, evaluating, and maintaining performant queries is a time-intensive undertaking. The terms most associated with AI/ML research in 2022 will be different from relevant terms in 2012" (p. 6). It can be assumed that the CSET keyword list will be updated in the foreseeable future. In contrast to the other studies considered here, which are one-off studies, the CSET list is continuously being complemented.

2.5 Zeta Alpha 2023: Current edge of AI research

While the studies considered so far have analyzed longer periods of time, there are a number of studies that focus on more recent developments in the field of AI. One of these studies was published by Zeta Alpha 2023 under the title "Must read: the 100 most cited AI papers in 2022" (Zeta Alpha 2023). It deals with the global AI research output between 2020 and 2023.

Zeta Alpha is a software company from Amsterdam that has been operating a digital platform on the topics of AI and neuroscience since 2019. Zeta Alpha calls its platform the "Neural Discovery Platform for AI and beyond" (www.zeta-alpha.com, see also Fadaee, Gureenkova, Barrera et al. 2020). Scientists can enter their research and interest profiles on the platform, and a weekly newsletter then alerts them to new publications in their respective research areas. In 2023, the company used its expertise in keywording and thematic clustering of research articles to characterize the research landscape based on the 100 most cited AI articles in 2020, 2021 and 2022.

It is rather unusual in bibliometric studies to count citations of articles published in the same year (plus the first three months of the following year, according to Zeta Alpha). However, if one accepts the argument that research in the field of AI is extremely dynamic and that current work is mainly based on the latest research results, it is nevertheless interesting to take a look at the method and results of Zeta Alpha's study.

The articles analyzed are articles that were published on the community platform ArXiv, i.e. preprints, as well as articles that are searchable via the Semantic Scholar platform. In addition to preprints, journal and conference articles are also available on the Semantic Scholar platform. The reason for focusing on these two platforms, according to Zeta Alpha is that current AI research is increasingly taking place outside of traditional publication formats. The explosive growth of these platforms speaks for their increasing relevance for the global AI research community.

The procedure for identifying the top 100 cited AI articles is relatively simple, as ArXiv and Semantic Scholar already offer rankings according to citations ("sort by relevance"/ "sort by citation count"/ "sort by most influential papers"). However, the number of citations is not thoroughly shown. Missing information was thus was added using the ArXiv API or by manual lookups via Google Scholar.

The results of the searches were evaluated with regard to the country distribution, the involved research institutions and the extent to which companies were involved (see the USA-China comparison in section 5.4).

Unfortunately, the published study by Zeta Alpha does not contain a more in-depth analysis of the content of the top 100 papers, which could provide information about the research topics of the community. However, an inquiry to Zeta Alpha revealed that there was an internal thematic clustering of the top 100 cited articles for the year 2022. This is because the top 100 articles - like all other AI articles analyzed for the company's own platform - were assigned to specific AI topics by Zeta Alpha. The corresponding tagging process was developed and refined by Zeta Alpha over several years. It is based on a machine learning process in which a so-called Statistical Named Entity Recognizer (NER) was trained with 1,000 possible AI concepts (see Fadaee, Gureenkova; Barrera et al. 2020, p. 2). The trained algorithm was then applied to new articles to classify them thematically.[6]

The analysis of the 100 most cited articles in 2022 results in a total of 45 AI topics. The topics are presented in varying degrees of detail, e.g. in the topic "Large Language Models LLMs" there are 10 subcategories (LLMs-Open Source, LLMs-Code Generation, LLMs-MLOps etc.), in the topic "Graph Neural Networks GNN" there is only one (GNN-Molecules). A summary of the topics on the first content level results in a total of 22 topics. According to Zeta Alpha, the 100 most cited AI articles in 2022 deal with the following topics (sorted by frequency of citation):

- Large Language Models (LLMs),
- Multimodal AI,
- Transformers,
- Reinforcement Learning,
- Diffusion Models for ML
- AI Image Generation,
- Convolutional Neural Network (CNN or ConvNet),
- AI for Protein Models,
- Deep learning,
- Computer Vision,
- Graph Neural Networks (GNN),
- DeepFakes,
- Machine Learning Operations (MLOps),
- Large-Scale Weak Supervision Learning,
- Imitation Learning – Robotics,
- Genetic Algorithm in Machine Learning – Robotics,
- Recurrent Neural Network (RNN) Robotics,
- AI for Tabular Data,

[6] Interview with Jakub Zavrel on 1.12. 2023 and personal communication with Mathias Parisot on 5.12.2023.

- AI Code Generation,
- AI Cyber Attack Detection,
- AI Nuclear Fusion Control,
- AI Social Media Analysis.

These 22 topics provide information on the AI subjects that were relevant for the AI community in 2022. Large language models, multimodal AI and transformers were of particular importance. Half of the 100 most-cited papers in 2022 dealt with these three topics.

However, no corresponding analyses are available for the years 2020 and 2021, and there is no corresponding evaluation for 2024 either. It is therefore not possible to carry out evaluations over several years to show topic trends. Zeta Alpha has recently started to produce monthly reports on the most relevant AI publications (see the "Trends in AI" series at www.zeta-alpha.com/blog-1) which indicates a high level of dynamism in the field.

There are also methodological limitations. Firstly, the focus on the years 2020-2022 means that all topics that were important in the past were more or less ignored. Secondly, it is unclear which of the identified articles will actually develop into high-impact articles and which will not. This is because 14 months is a very short period of time for measuring citation rates. It is well known that good research needs time to be noticed by the community; the longer the period of time considered, the more citations can be expected for important publications.

2.6 Würzburg Group 2023: AI topic areas

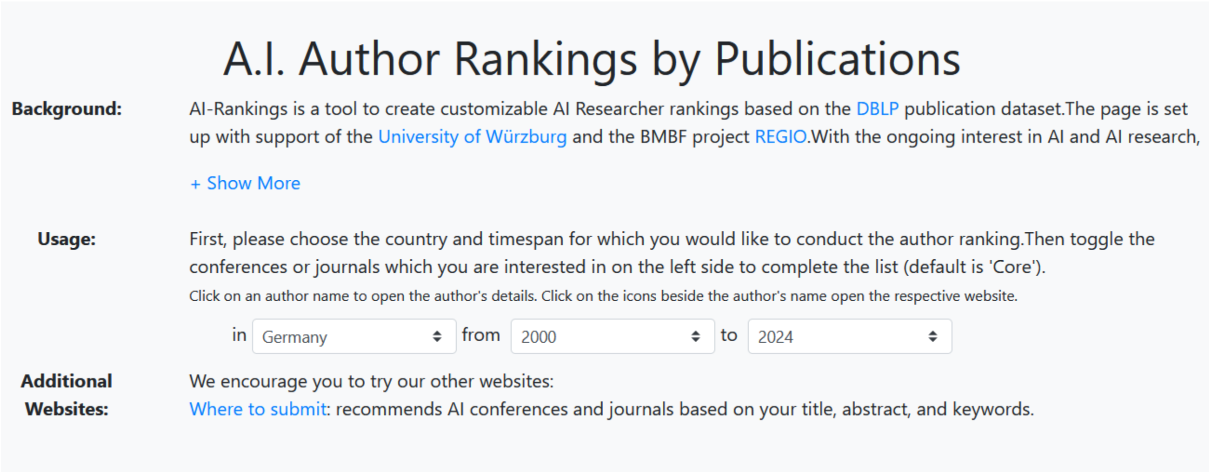
An interesting approach to structuring AI research and measuring research output has been implemented by a group of computer scientists at the University of Würzburg with the web tool "A.I. Author Rankings by Publications" (https://airankings.professor-x.de). The web tool is based on data from the computer science literature database dblp (database systems and logic programming, https://dblp.uni-trier.de), which is operated by the University of Trier and the Leibnitz Center for Informatics Schloss Dagstuhl. The dblp database now contains more than seven million entries[7] of scientific articles in the field of computer science that have been published in international journals and at conferences. It also contains monographs and entries from repositories, such as the Computing Research Repository (CoRR, but not from ArXive). The dblp database is used by around 750,000 scientists from all over the world every month. The dblp team curates large parts of the database and also provides an API for specific evaluations.

The background to the Würzburg group's "A.I. Author Ranking" web tool was the desire to obtain a quick and up-to-date overview of who is conducting research in which AI research fields and how relevant the respective research work is (source: https://airankings.professor-x.de). While the dblp database could be used for the former, an auxiliary variable had to be used for the question of relevance, namely the h-index of the respective authors. The h-index is reported by Semantic Scholar and was combined with the dblp data by the Würzburg researchers.

A simple search mask (see Figure 1) can be used to select the country and the time period to which the query should refer.

[7] https://blog.dblp.org/2024/01/01/7-million-publications/

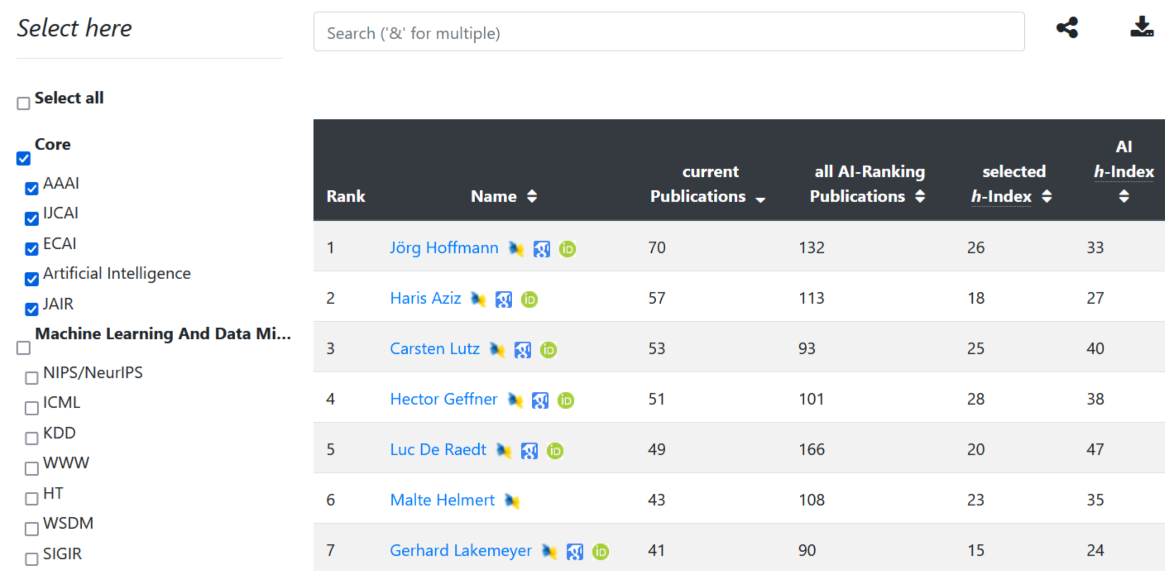
Figure 1: Screenshot of the query mask for the AI author rankings by publications



Source: https://airankings.professor-x.de

As a result, the tool displays the names of scientists who publish in the field of artificial intelligence, the number of publications and the h-index of each person (see Figure 2).

Figure 2: Result list of a query in the web tool AI author rankings by publications



Rank	Name	current Publications	all AI-Ranking Publications	selected *h*-Index	AI *h*-Index
1	Jörg Hoffmann	70	132	26	33
2	Haris Aziz	57	113	18	27
3	Carsten Lutz	53	93	25	40
4	Hector Geffner	51	101	28	38
5	Luc De Raedt	49	166	20	47
6	Malte Helmert	43	108	23	35
7	Gerhard Lakemeyer	41	90	15	24

Source: https://airankings.professor-x.de

In addition to the selection of country and time period, the tool enables a narrowing down to a specific AI research field. This narrowing down is done by selecting journals and conference publications, which the Würzburg group has grouped into nine subject areas. The basis for the thematic grouping was the classification used in the international standard AI textbook by Russel and Norvig (Kersting et al. 2019). This classification of the AI research field has the advantage that it reflects both symbolic AI (today often referred to as "good old-fashioned AI", see Morris et al. 2023) and statistical AI (especially machine learning and LLMs, see section 2.7).

The AI topic areas are:

- Artificial Intelligence (Core),
- Problem solving,
- Knowledge representation and reasoning,

- Uncertainty in AI, Probabilistic Models,
- Machine learning and mata mining,
- Computer Vision,
- Natural Language Processing, Computational Linguistics,
- Human-machine interactions,
- Robotics,
- AI and Ethics.

With the help of the data structured in this way, it would in principle be possible to carry out a country-specific evaluation for each of the nine AI research fields and thus to display detailed research profiles. [8] However, such an analysis currently do not exist.

What is available, however, is a count of the number of AI publications across all areas by country (publications from 2013 to 2022), which was carried out by Brühl (2023) for the journal Wirtschaftsdienst (see section 5.5). One problem that arises with the evaluations via this web tool is that the data is personal. Brühl notes: "We have also compiled rankings of researchers according to the various AI segments, but have not published them here, as this is not about the individual excellence of researchers in a specific field, but rather an indicator of research productivity in the field of AI as a whole" (Brühl 2023, p. 522). Any further evaluation would therefore have to be carried out with aggregated data without reference to individuals.

2.7 NLLG 2023: Focus on language models

The importance of large language models, multimodal AI and transformer models for current AI research is confirmed and further specified by a study by the Natural Language Learning Group (NLLG) at the University of Mannheim. Their study was published on ArXiv in December 2023 under the title "What are the most influential current AI Papers?" (Zhang et al. 2023). The Natural Language Learning Group is a group of researchers applying bibliometric methods to provide other AI researchers and experts with guidance in a dynamic research environment. To this end, the 40 most cited AI articles published on ArXiv in 2023 were identified and analyzed.

Similar to the Zeta Alpha analysis, which covers the period from January 2022 to March 2023, the NLLG analysis looks at a very short period. The NLL Group focuses on the period between January and September 2023. Its analyses are based on 47,331 articles that were published in the selected period in the ArXiv-subcategories of Computer Science (CS), Artificial Intelligence (cs.AI), Computer Vision and Pattern Recognition (cs.CV), Natural Language Processing (cs.CL) and Machine Learning (cs.LG). The citation analysis was performed using Semantic Scholar counts, which were normalized by the group using the Newman Z-score (see Zhang et al. 2023, p. 3). Normalization is necessary to eliminate cumulative effects that arise when an article appears early in the period under consideration and thus has more time to be cited.

The list of the 40 most cited AI articles in the first three quarters of 2023 is reproduced in Zahng et al. 2023 with the respective title, publication date and citation values. The list is headed by a technical article on ChatGPT, in which Open AI employees document, among other things, how they have trained ChatGPT to respond in a socially undesirable way. The article received 1,573 citations and a Z-score of 35.1 in the period under review, followed in second place with 778 citations and a Z-score of 34.3 by an article on the fine-tuning of Llama 2.

[8] According to the Würburg Group, the XML dump of the dblp does contain information about affiliations and their location. This information could be used to create country profiles for the AI subject areas used. Email communication from September 23, 2024 with the Data Science Chair of the University of Würzburg.

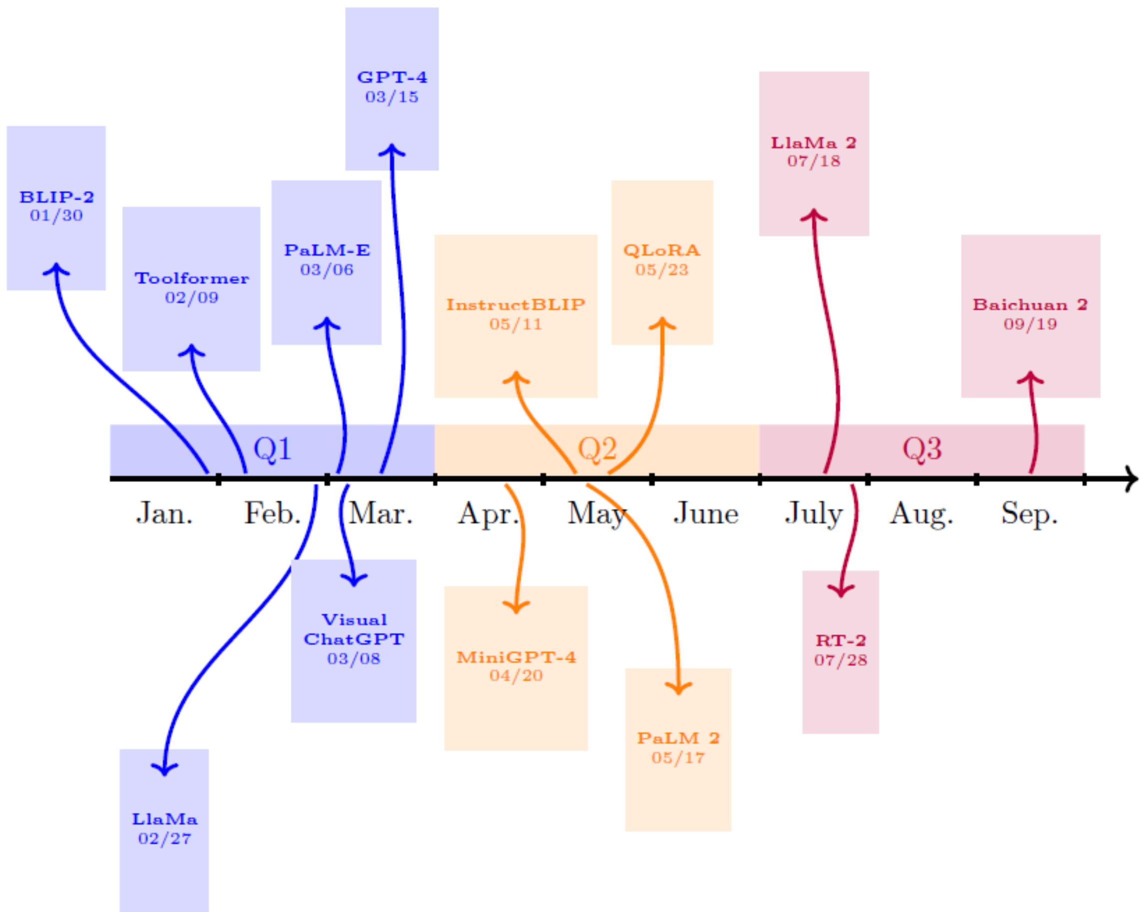
Taken as a whole, the 40 most-cited articles in 2023 deal with topics that can be described using these five keywords:

- LLM,
- ChatGPT,
- GPT,
- LlaMA,
- Multimodality (Zhang et al. 2023, p. 13).

In fact, the keyword LLM covers 90% of all top 40 articles: 36 of the 40 most cited papers deal with large language models. This AI research topic is listed in the Arxiv database in the Natural Language Processing (NLP) category. It is interesting to compare the published and cited articles: While only 16% of all articles published on ArXiv have NLP as their main category, 50% of the most cited papers have NLP as their primary category. And of these papers, 90% deal with LLMs. This shows the current dominance of the AI research field of NLP and large language models.

Zhang et al. 2023 also show which language models received particular attention from AI researchers in the first three quarters of 2023 (see Figure 3)

Figure 3: Influential AI models and techniques in 2023 according to Zhang et al. 2023



Source: Zhang et al. 2023, p. 2.[9]

[9] The explanation in the original reads: "Timeline of influential models and techniques from our top-40 list based on normalized citation counts. The height of each node is related to the corresponding rank".

The analysis of the NLL group shows the paramount importance of language models in current AI research. Despite a more sophisticated methodology, however, the same limitations apply here as in the analysis of Zeta Alpha: a large part of AI research is ignored because the selected time period only covers the past year. However, the study draws attention to specific language models and their significance for the AI community.

2.8 OECD.ai: Focus on application

The OECD's "Live Data" web tool (https://oecd.ai) offers a special focus on AI applications such as robotics or automation. The visualization tool is based on two data sources, the literature database OpenAlex (https://openalex.org) and the Scopus database from Elsevier (www.scopus.com).

Various queries can be sent to the OECD web tool under the menu item "AI Research", such as which countries have published the most AI articles in the last 10 years ("AI research publications time series by country"). This query, as well as the other selection options shown in Table 7, access the OpenAlex dataset.

Table 7: Screenshot of the query options on the OECD "Live Data" web tool based on OpenAlex data

Countries	Institutions	Topics
AI research publications vs GDP per capita by country, region, in time (OpenAlex)	AI research publication time series by institution	AI Research by publication type
AI research publications time series by country	AI research publication types by institution	AI publications by academic discpline
Top countries in AI research publications in time	Collaboration in AI research publications within & between institutions	Trends in AIresearch application areas by country
AI research publication types by country	AI research networks by institution	Top countries by AI research application area
Domestic and international collaboration in AI research publications	AI research publications map	Top countries in AI research publications by policy area
AI research country network		Top policy areas in AI research publications by country
		Top concepts in AI research publications by policy area

Source: https://oecd.ai/en/data?selectedArea=ai-research

Similar queries are possible in the second area, here, however, the visualization tool uses Scopus as the data basis. A special feature of Scopus is that it allows queries according to the gender of authors (see Table 8).

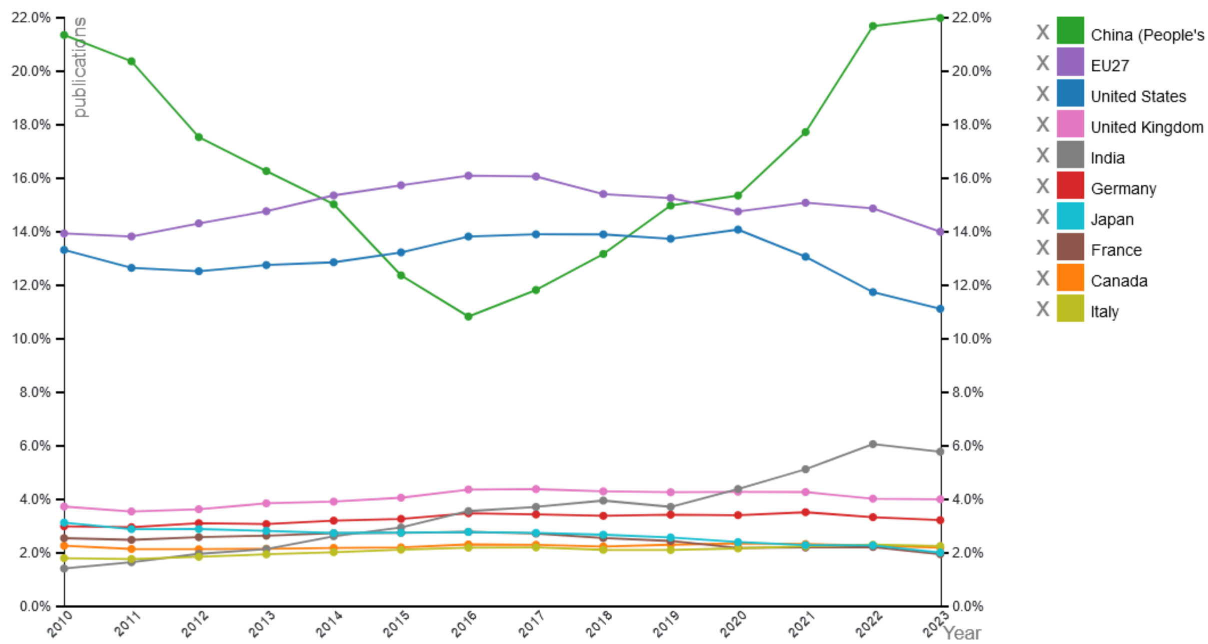
Table 8: Screenshot of the query options on the OECD "Live Data" web tool based on Scopus data

Countries	Gender	Institutions
AI publications vs GDP per capita by country, region, over time (Scopus)	Number of research publications in AI by gender	AI publications time series by institution
AI publications time series by country	Number of research publications in AI by gender and country	AI publication types by institution
Top countries in AI publications in time	Share of women in AI publications by country	Collaboration in AI publications within & between institutions
AI publication types by country	Share of men in AI research publications by country	**Topics**
Domestic and international collaboration in AI publications	AI research publications exclusively written by each gender	AI publications by subject area
		Trends on AI subtopics over time

Source: https://oecd.ai/en/data?selectedArea=ai-research

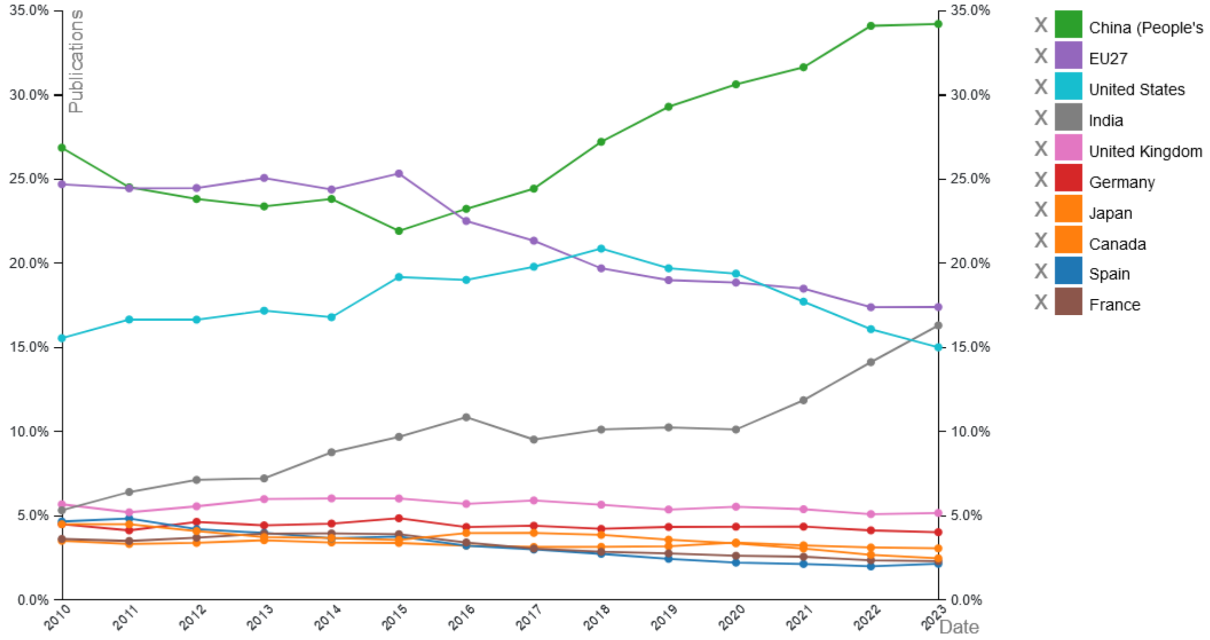
To display the countries with the most AI publications the entry point "Top countries in AI publications in time" in both areas is be used. Comparing the results on the question of which country most AI publications come from, there are only slight differences between the OpenAlex and Scopus data (Figs. 4 and 5).

Figure 4: "AI publications time series by country": Share of the top 10 countries in all AI publications between 2010-2023 Data from OpenAlex



Source: OECD.ai, basis: OpenAlex, retrieved on 24.9.2024

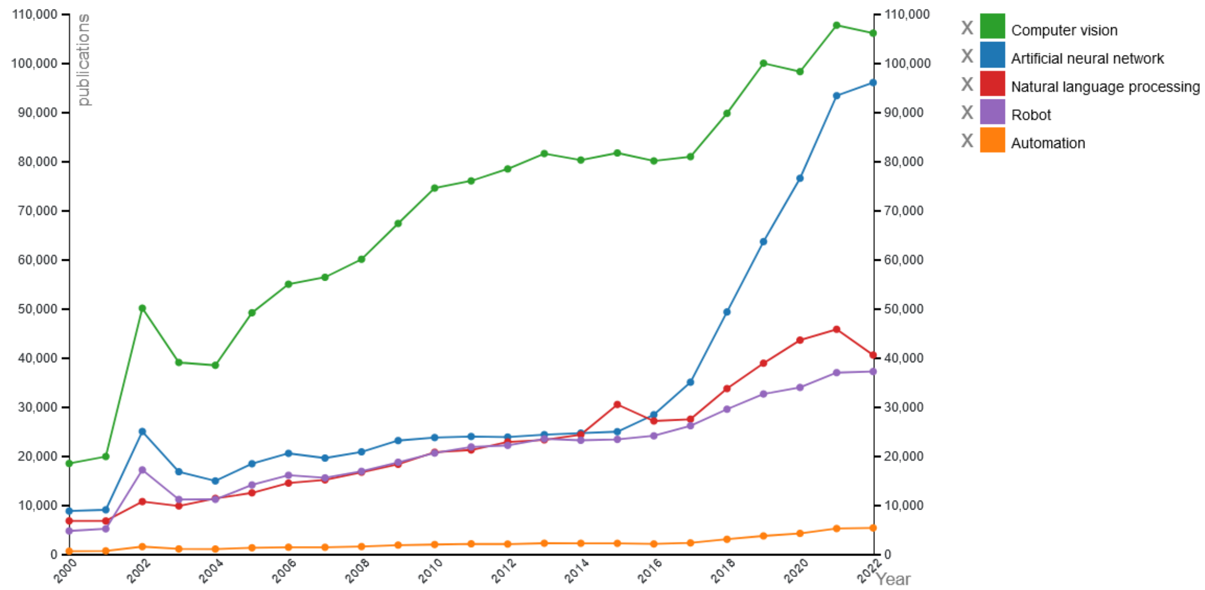
Figure 5: "AI research publications time series by country": Share of the top 10 countries in all AI publications between 2010-2023. Data from Scopus



Source: OECD.ai, basis: Scopus, retrieved on 24.9.2024

The OECD data draws attention to the importance of AI fields of application: Not only basic computer science research with the development of complex ML models or the optimization of learning processes play an important role in the innovation process, but also implementations in application fields such as robotics, automation or in the healthcare sector (Figure 6).

Figure 6: Trends in AI research application areas, publications, all countries 2000-2022

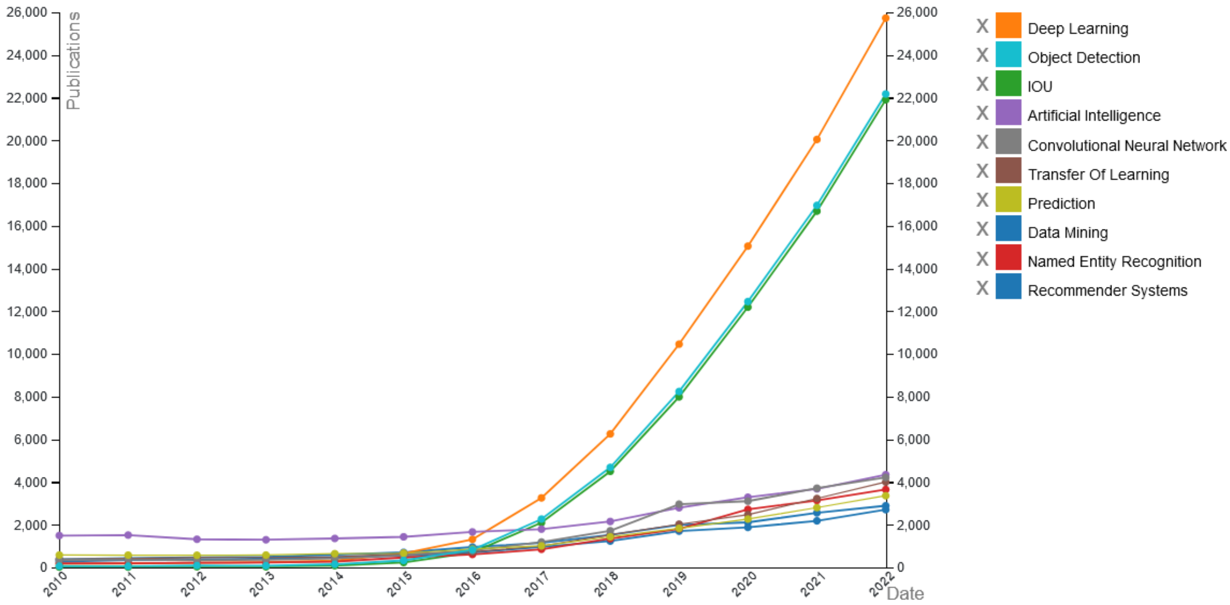


Source: OECD.ai, data: OpenAlex, retrieved on 24.9.2024

Important AI research is also being carried out in these fields of application, which remains hidden if only basic research is considered. Bibliometrically, this can be brought to light by combining keywords, as the OECD does with the areas of robotics and automation.

Another methodological finding from the analysis of the OECD data is that AI-based topic modeling methods or automated classifications into research fields are not always helpful or accurate. Figure 7 shows the top 10 AI research fields and their development since 2010.

Figure 7: Trends on AI subtopics over time, data from Scopus (2010-2022)



Source: OECD.ai, basis: Scopus, retrieved on 24.9.2024

The methodological note under the graphic reads: "Data downloads provide a snapshot in time. Caution is advised when comparing different versions of the data, as the AI-related concepts identified by the machine learning algorithm may evolve in time."

While AI research areas such as "Deep Learning", "Object Detection" or "Data Mining" are comprehensible, it is questionable why IOU[10] appears here. Also, "Prediction" which is a very general term, only generates a few hits. A keywords search in OpenAlex (https://openalex.org) yields completely different results.[11]

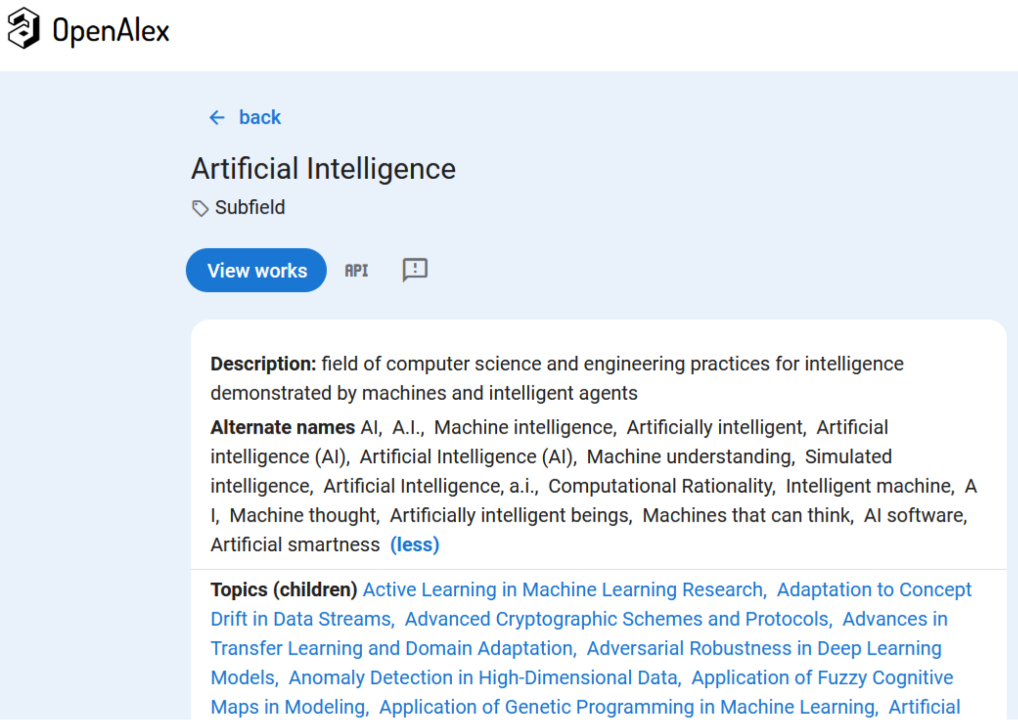
It is also possible to display additional topics in the OECD tool, which can be selected via the pull-down list ("add topic"). However, for many of the topics that can be selected there, an AI reference is not directly recognizable, including topics such as "ACS Aircraft" or "Zebrafish". If these topics are selected, only a few hits are found in the OECD evaluation, but Elsevier's algorithm apparently identified them as AI sub-areas.

An alternative is offered by OpenAlex, the other OECD source. The topics ("children") generated by OpenAlex with the help of AI are more specific and directly related to AI (Figure 8).

[10] Intersection-over-Union (IoU) deals with the evaluation of the overlap between two areas in image processing and object tracking. It is often used to measure the accuracy of object recognition models. While Scopus shows around 22,000 publications on this topic for the year 2022 in the chart above, OpenAlex, with its far more extensive database, only found 2,204 publications on IoU in the same year (full-text search with the combination: 2nd intersection-over-union AND "artificial intelligence").

[11] Prediction AND "Artificial Intelligence" generates 36,150 hits in OpenAlex for the year 2022.

Figure 8: AI-generated AI topics according to OpenAlex (excerpt)



Source: OpenAlex.org, for the method see "OpenAlex: End-to-End Process for Topic Classification", https://docs.openalex.org/api-entities/topics, accessed September 20, 2024.

It is worth taking a look at the total of 76 OpenAlex topics because they contain many specific application combinations that are derived directly from the various AI research areas (Figure 8 shows an excerpt from the keyword list).

3 Analysis of the classification of ML models

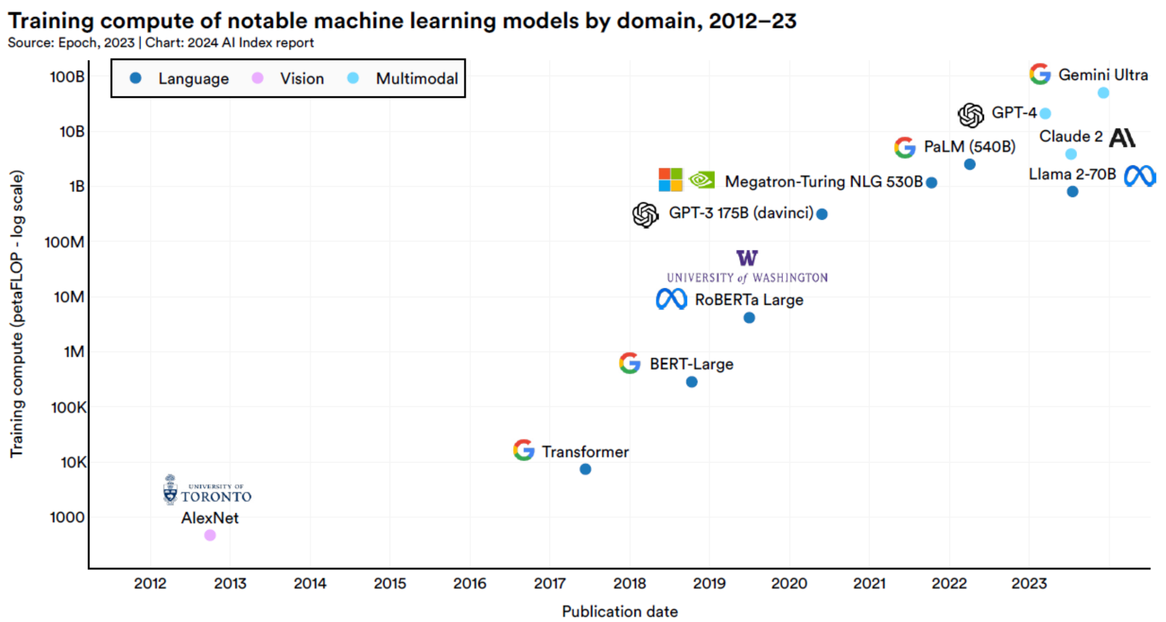
3.1 Epoch 2024: Detailed analysis of ML systems

Epoch AI is a private research initiative dedicated to the documentation and evaluation of machine leaning (ML) models[12] (https://epochai.org). In contrast to the studies examined so far, Epoch data is not bibliometric data, but data on ML models that have been evaluated individually by experts.

Since ML models were already mentioned in the Zeta Alpha and NLLG studies and corresponding keywords were listed, the presentation of the Epoch AI results does not serve to expand the AI keyword list. Rather, the analysis of the Epoch data provides further indications of quality differences in AI research because ML models, including language models, can have different performance levels.

Since 2022, a 13-member Epoch AI expert group has been evaluating ML models in terms of the computational power ("compute") required and the size of the training data set used. Thousands of research articles have been analyzed for this purpose. In addition, the team documents the authors' affiliation to institutions, their nationality, research collaborations, etc. and enters this information into a database. This database now contains evaluations for 800 ML models that were developed between 2003 and 2024 (Hensall 2024).

Figure 9: Development of computing capacities for training machine learning models since 2012



Source: AI Index Report 2024, p. 51.

To be included in the Epoch AI database, an ML model must fulfill the following criteria: There must be documentation of the model, the model must contain a learning component, i.e. it must not be a "non-learned algorithm", and it must have been trained with data, i.e. it must be more than a purely theoretical description (see Epoch AI 2024). In addition, the model must meet the following

[12] Machine learning models are algorithms that learn from data in order to make predictions or decisions. They can be used for various tasks, such as image classification, recommendation systems or language processing.

notability criteria: It must have been cited over 1,000 times in literature, the training costs must exceed 5 million US dollars and it must have more than 1 million active users per month.

The AI Index Report of 2024 presents various analyses of Epoch AI data, including how the computing capacity requirements for the training ("training compute") of selected ML models have developed since 2012 (see Figure 9). The graph shows that powerful ML models require computing capacities beyond 1 million pentaFLOPS.

And Figure 10 shows that the so-called "deep learning era" only began in 2010, although machine learning models have been around since the 1960s.

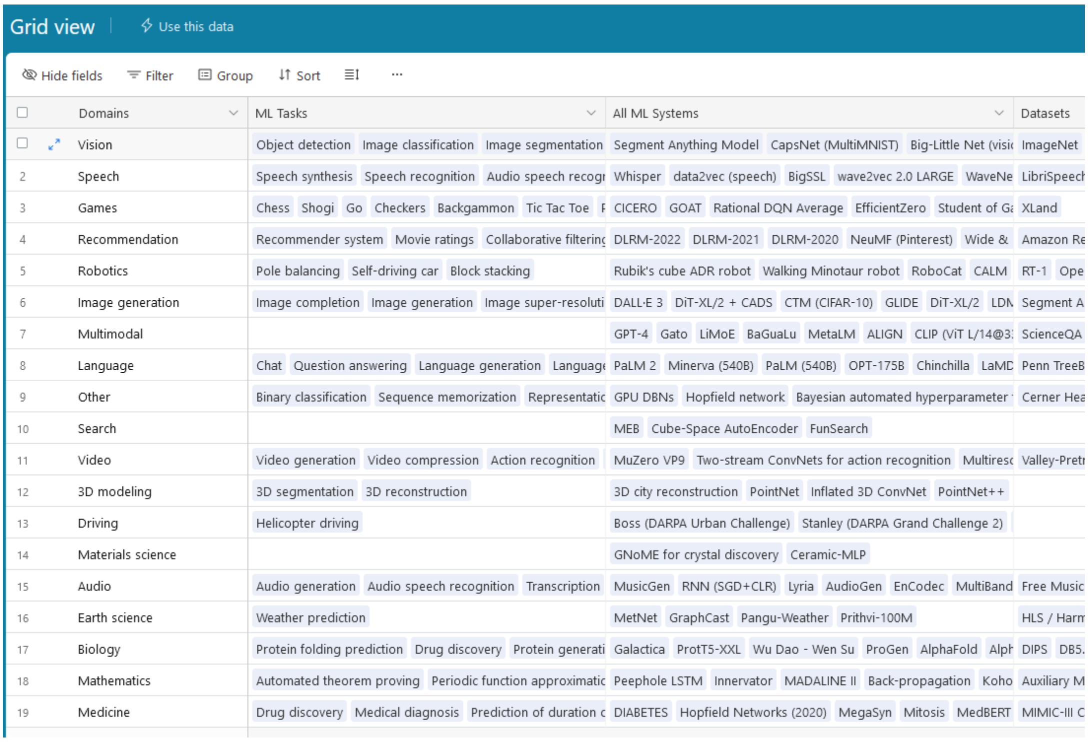
Figure 10: Relevant AI models ("notable AI models") according to Epoch AI since 1950

Source: https://epochai.org/data/notable-ai-models

The ML model "AlexNet" is highlighted in color in the figure because it is the ML model described by Alex Krizhevsky, Ilya Sutskever and Geoffrey Hinton in their 2012 paper "ImageNet Classification with Deep Convolutional Neural Networks", which is commonly regarded as the beginning of the new era in AI development (see e.g. Boqiang & Henry 2024).

All ML models documented by Epoch AI are assigned to so-called "domains", i.e. to research and application fields within which they were developed. Figure 11 shows a screenshot of the Epoch AI database, in which all 18 domains are listed. Not all domains are equally relevant; in some there are few ML models, in others many. If we summarize the most important domains, we can see that by far the most ML models have been developed in the areas of "Language" and "Vision" in recent years (see Figure 12).

Figure 11: Screenshot of the Epoch AI database with relevant ML models and their assignment to application fields or "domains"



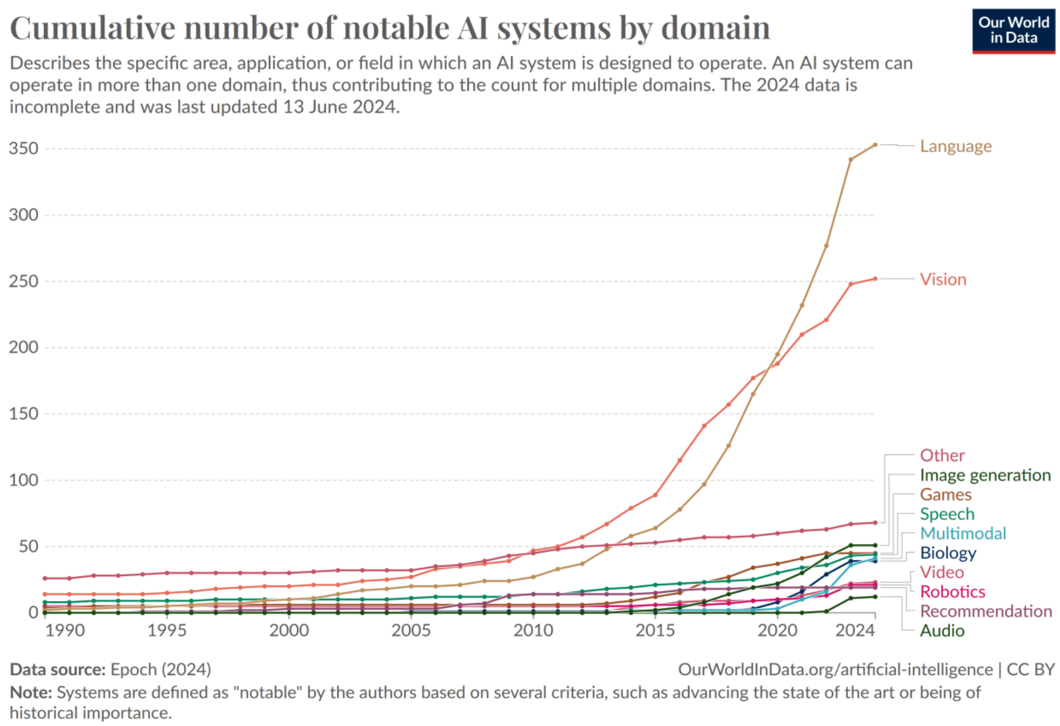
Grid view | Use this data

Hide fields | Filter | Group | Sort | ...

	Domains	ML Tasks	All ML Systems	Datasets
	Vision	Object detection, Image classification, Image segmentation	Segment Anything Model, CapsNet (MultiMNIST), Big-Little Net (visi	ImageNet
2	Speech	Speech synthesis, Speech recognition, Audio speech recogi	Whisper, data2vec (speech), BigSSL, wave2vec 2.0 LARGE, WaveNe	LibriSpeech
3	Games	Chess, Shogi, Go, Checkers, Backgammon, Tic Tac Toe, F	CICERO, GOAT, Rational DQN Average, EfficientZero, Student of Ga	XLand
4	Recommendation	Recommender system, Movie ratings, Collaborative filtering	DLRM-2022, DLRM-2021, DLRM-2020, NeuMF (Pinterest), Wide &	Amazon Re
5	Robotics	Pole balancing, Self-driving car, Block stacking	Rubik's cube ADR robot, Walking Minotaur robot, RoboCat, CALM	RT-1, Ope
6	Image generation	Image completion, Image generation, Image super-resoluti	DALL·E 3, DiT-XL/2 + CADS, CTM (CIFAR-10), GLIDE, DiT-XL/2, LDN	Segment A
7	Multimodal		GPT-4, Gato, LiMoE, BaGuaLu, MetaLM, ALIGN, CLIP (ViT L/14@3	ScienceQA
8	Language	Chat, Question answering, Language generation, Language	PaLM 2, Minerva (540B), PaLM (540B), OPT-175B, Chinchilla, LaMD	Penn TreeB
9	Other	Binary classification, Sequence memorization, Representatic	GPU DBNs, Hopfield network, Bayesian automated hyperparameter	Cerner Hea
10	Search		MEB, Cube-Space AutoEncoder, FunSearch	
11	Video	Video generation, Video compression, Action recognition	MuZero VP9, Two-stream ConvNets for action recognition, Multiresc	Valley-Pretr
12	3D modeling	3D segmentation, 3D reconstruction	3D city reconstruction, PointNet, Inflated 3D ConvNet, PointNet++	
13	Driving	Helicopter driving	Boss (DARPA Urban Challenge), Stanley (DARPA Grand Challenge 2)	
14	Materials science		GNoME for crystal discovery, Ceramic-MLP	
15	Audio	Audio generation, Audio speech recognition, Transcription	MusicGen, RNN (SGD+CLR), Lyria, AudioGen, EnCodec, MultiBand	Free Music
16	Earth science	Weather prediction	MetNet, GraphCast, Pangu-Weather, Prithvi-100M	HLS / Harm
17	Biology	Protein folding prediction, Drug discovery, Protein generati	Galactica, ProtT5-XXL, Wu Dao - Wen Su, ProGen, AlphaFold, Alph	DIPS, DB5.
18	Mathematics	Automated theorem proving, Periodic function approximatic	Peephole LSTM, Innervator, MADALINE II, Back-propagation, Koho	Auxiliary M
19	Medicine	Drug discovery, Medical diagnosis, Prediction of duration c	DIABETES, Hopfield Networks (2020), MegaSyn, Mitosis, MedBERT	MIMIC-III C

Source: https://airtable.com/appDFXXgaG1xLtXGL/shrhzolGiQCVnwOY5/tbleYEsZORsiYRVTM, reference form the Epoch website: https://epochai.org/data/epochdb/documentation.

Figure 12: Cumulative number of relevant ML models by domain since 1990



Source: Epoch AI, https://ourworldindata.org/grapher/share-of-ai-systems-by-domain

The following list, taken from the documentation page of the Epoch AI database, explains the domains in more detail:

- **Vision**: Software for image labeling and picture identification
- **Speech**: Interactive voice response systems and models that comprehend and produce spoken language
- **Games**: Models that acquire the skills to compete against proficient adversaries in games
- **Recommendation** systems offer suggestions based on user preferences, prominently seen in online shopping and media streaming. For instance, Netflix's movie suggestions or Amazon's product recommendations are powered by algorithms that analyze users' preferences and past behaviors.
- **Robotics** systems combine AI with mechanical engineering to create autonomous robots for various industries.
- **Image Generation**: Systems that convert text instructions into visuals (such as DALL-E, Fotor, MidJourney)
- **Multimodal**: Systems that amalgamate text, visuals, and sound (like ChatGPT, Microsoft CoPilot, Google Bard/Gemini)
- **Language**: Models that comprehend and convert language (like Google Translate, DeepL, Microsoft Translate)
- **Other**: Models for 3D visualization, self-driving technology, audio and video manipulation, and search optimization algorithms
- **Biology**: Models developed for scientific research and studies.
- **Video** systems analyze and generate video content, aiding in editing, surveillance, and content creation.
- **Audio** systems process and generate sound, with applications in music composition, signal processing, and sound recognition.

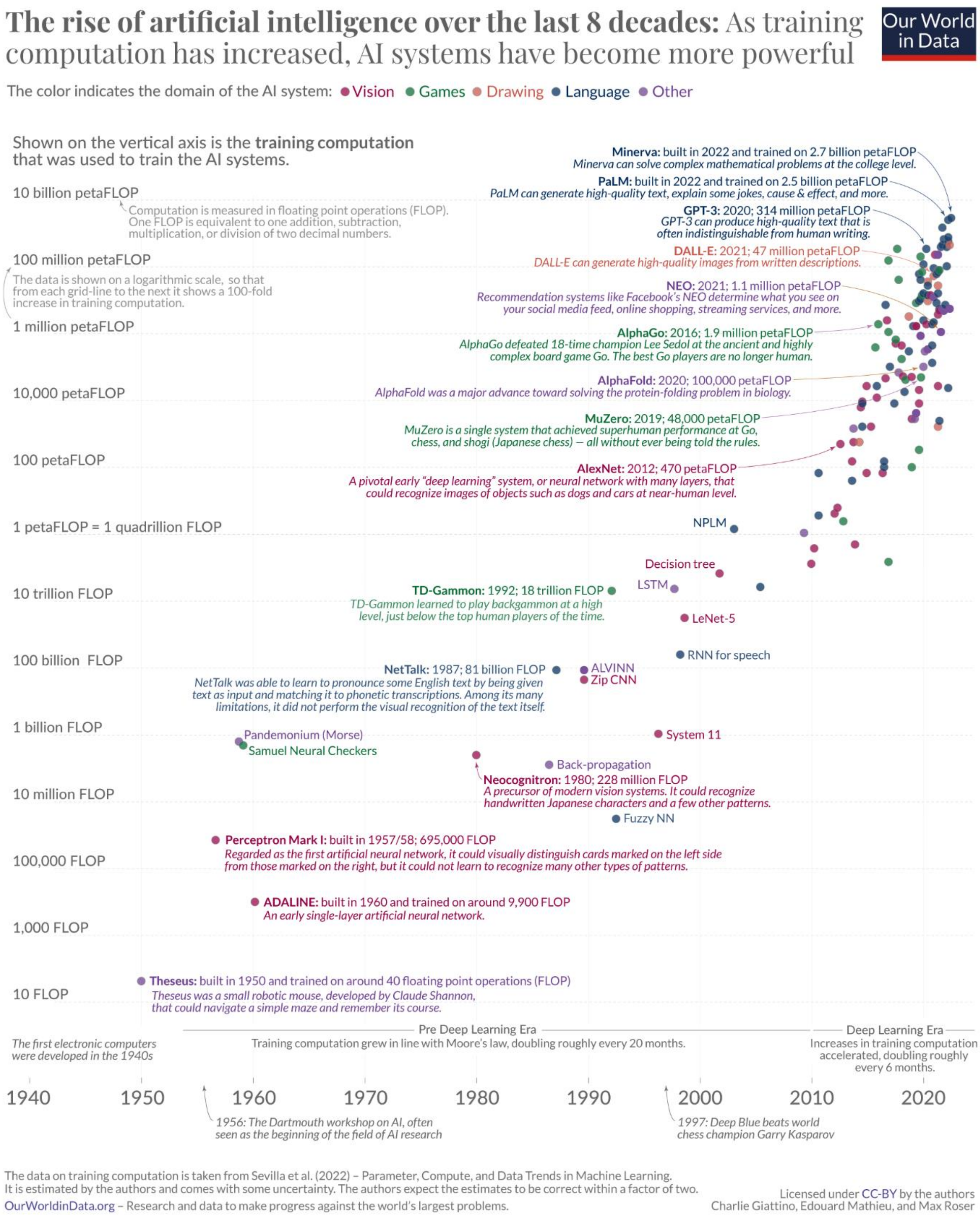
In addition to the thematic classification of current AI developments, the Epoch AI data offers the opportunity to rank ML models according to their requirements: ML models can be considered mire advanced the more computer computing capacity is required for training. This is a relatively simple parameter that can also be expressed in terms of cost.

And indeed, this quantitative measure has been used to evaluate AI models in current regulation: both the European AI Act and the US Executive Order on AI follow this approach and have defined thresholds for computing capacity above which stricter rules for language models apply. "Epoch AI's database of AI models has been an invaluable resource for policymakers making such endeavors, says Lennart Heim, a researcher at nonprofit think tank the RAND Corporation (...) 'I think then it's fair to say there is no other database in the world which is that exhaustive and rigorous.'" (Hensall 2024).

A detailed illustration of the development of required computing capacities is shown in Figure 13.[13]

[13] For the meaning of FLOPS, see e.g. Heim 2023

Figure 13: Development of computing capacities for the training of ML models



Source: Roser 2022 on the basis of Epoch AI data

Ranking on the basis of computing power has the advantage that the data is easy to collect. However, the method has its limits, firstly because computing capacity cannot be increased endlessly and secondly because there may be models in the future that require less computing power for the same performance.[14]

Furthermore, only the large language models are considered here. However, there are many other specialized ML models that require less computing power but can still perform highly complex, demanding tasks. While LLMs are "generalists", capable of handling many different tasks, specialized AI models are trained with domain knowledge and can be used, for example, in the fields of medicine, production, logistics and so on. It is currently unclear which direction the development will take. There are areas in which specialized models are superior to large language models (see e.g. Drinkall et al. 2024) and there are combinations of LLMs and specialized ML models (see e.g. Goncalves). This means that looking at the large language models alone is not enough to determine high-quality AI.

It should also be mentioned that, in addition to rankings based on computing capacity for training, there are other technical methods for determining high-performance AI. Since the emergence of large language models, various performance-based approaches have been developed in the AI community, most of which work with accuracy values. This involves determining accuracy and precision in classification tasks, answering questions on a closed text basis, argumentation and reasoning, reading comprehension and inference (see e.g. Hahn 2023, Aleph Alpha 2023 or Zhang, Michael 2023).

However, performance-based rankings of ML models have their own limitations. On the one hand, no standard method has yet been established in the community, and on the other, minor changes to the algorithm or new combinations of training data pools can have a great impact on performance. The accuracy value often used in the AI community for language models therefore fluctuates from version to version and is therefore also only suitable as a benchmark for ranking AI models to a limited extent.

In summary, it can be stated that the current rankings of AI systems are rather short-lived due to the highly dynamic nature of research and development. The assessments of which models or research groups are currently leading change in rapid succession, meaning that top positions resemble a challenge cup that often has to be passed on to others (Wasner 2024). And there is also a lot of methodological flux; the AI Index Report concludes that the evaluation of AI models is currently "somewhat subjective".[15]

[14] For example, version o1 of Open AI´s ChatGPT presented in September 2024 requires less computing power for training, but more for interference. Nevertheless, ChatGPT o1 has higher performance values than all previous GPT models (see White 2024).

[15] "Admittedly what constitutes advanced or frontier research is somewhat subjective. Frontier research could reflect a model posing a new state-of-the-art result on a benchmark, introducing a meaningful new architecture, or exercising some impressive capabilities." (AI Index Report 2024, p. 19)

4 Summary of the results and presentation of the ISI list

The aim of the analysis was to firstly develop a keyword-based basic definition of the research field of AI that can be used to describe the entire research area while minimizing the number of false hits. Secondly, the question was investigated as to whether quality levels can be distinguished in AI technologies and, if so, which keywords can be used to distinguish sophisticated AI from standard AI.

For this purpose, eight relevant bibliometric studies and the Epoch classification scheme of ML systems were analyzed. Keywords or keyword sets were taken from these sources for our own list. It became apparent that none of the existing keyword lists could be used without changes or additions. The studies analyzed were either published before the boom in machine learning and large language models and therefore underestimated or even ignored these fields of research. Or they were published afterwards and focused only on these new fields, thus ignoring those AI areas that are older but still represent relevant AI research today and could become important in the future.

Step by step, our own list of keywords was compiled that covers both current and long-established fields of artificial intelligence research. In addition, terms such as "robotics" or "automation" were included to reflect the fact that AI research encompasses not only basic computer science research, but also application-oriented research.

In addition to analyzing existing studies, a total of 18 expert interviews were conducted. The interviews also contributed keywords for our own list as well as insights into how to distinguish quality levels.

It turned out that there is a spectrum of AI technologies ranging from rule-based systems, expert systems and knowledge ontologies to machine learning and natural language processing. This spectrum is complex because the technologies used are often combined and high-performance systems make use of different technologies.

Although starting points for distinguishing between complex and simple AI could be identified, it turned out that each distinction in itself is incomplete, provisional or cannot be generalized. As a result, it is necessary to approach the differentiation of AI quality levels specifically and to determine quality measures specifically and with regard to the respective question.

The keyword list created can be used as a starting point for this, as it covers the entire spectrum of AI technologies: Keywords in the list such as "hybrid AI" already indicate sophisticated AI. Also, combinations of keywords in the list can be used to identify sophisticated AI. In addition, combinations with terms such as "high performance computing", "complex setting", "advanced machine learning" etc. can be used to specifically describe higher quality levels.

The list created was tested and sharpened in trial runs - keywords with very few hits were removed, keywords with an unexpectedly high number of unspecific hits were supplemented with AND links. Finally, our own results were compared with partial results from other studies to check their plausibility. Table 9 shows the ISI keyword list with a total of 19 main entries and 72 subentries.

Table 9: ISI keyword list for defining the research field "artificial intelligence"

0 Artificial intellgence
1 Machine Learning
2 Deep learning
3 Artificial Neural Network*
deep neural network*, convolutional neural network*, graph neural network*, recurrent neural network*, genetic algorithm*, evolutionary algorithm* evolving fuzzy clustering, classification algorithm*, predict* AND model* AND artificial intelligence, support vector machine, supervised learning, semi-supervised learning, random forest, inference learning, AutoML, protein AND artificial intelligence
4 Unsupervised learning
feature selection AND machine learning, feature engineering, autoencoder, q-learning, policy gradient method, federated learning, meta-learning
5 Reinforcement learning
6 Transfer learning AND machine learning
domain adaptation AND machine learning, hybrid AI
7 Natural language processing
natural language understanding, machine translation, feature extraction AND artificial intelligence, speech-to-text, multimodal AND AI, multimodal AND LLM, chatbot*
8 Generative AI
large language models, foundation models, generative adversarial networks, synthetic data AND deep learning, *shot learning, self-attention generative, retrieval\-augmented generat%, multimodal AND artificial intelligence
9 Computer vision
pattern recognition AND artificial intelligence, image recognition AND artificial intelligence, image classification, fac* recognition, image processing AND deep learning, video analysis AND artificial intelligence, object recognition, AND artificial intelligence, action recognition AND artificial intelligence. Cyber\- attack AND artificial intelligence
10 Explainable AI
responsible AI, trustworthy AI, AI ethics, neurosymbolic
11 Big data analytics
12 Knowledge Graph*
knowledge representation AND AI, ontology-based AND AI, problem solving AND AI, Uncertainty AND AI
13 Logical reasoning AI
fuzzy logic AND AI
14 Decision Support System*
expert systems AND information systems, case-based reasoning, recommender system*, automated decision making
15 Computational Neuroscience
16 Artificial General Intelligence
general AI, human-level AI
17 AI for Robotics
developmental robotics, embodied AI, humanoid robot*, mobile robot*, imitation learning AND robot*, computational intelligence, automation AND AI
18 Quantum comput* AND AI

Source: Fraunhofer ISI, as of September 25, 2024

The difference to other AI keyword lists can be summarized as follows:

- The ISI list covers both the established AI research areas (symbolic AI) and the ML-based research fields that are currently in the foreground (statistical AI).
- It contains some of the most important fields of application (robotics, automation, facial recognition, machine translation, etc.), which are also important for the development of AI technologies in addition to basic research.
- With "hybrid AI", "embodied AI", "transfer learning" AND AI or multimodal AND "artificial intelligence", it contains keywords or keyword combinations that indicate high-level AI. In a second step, the list can be used as a basis for further analyses in which individual keywords are combined with terms that in turn imply high quality levels, such as "high performance computing", "complex setting", "advanced machine learning", etc.

Although the ISI keyword list was compiled with great care and taking into account bibliometric and content-related AI expertise, it is also a time-dependent snapshot of the AI development. The analysis has shown that AI development is extremely dynamic and is characterized in part by leaps in innovation that cannot be predicted. This list is dated November 2024 and must be continuously reviewed and, if necessary, updated to include the latest developments.

5 Country comparisons and research profiles

After the analysis of bibliometric classifications of AI, the results of the country comparisons are presented and analyzed in this section. The focus is initially on the China-USA comparison. The second part then focuses on European countries and attempts to determine an AI research profile for Europe with the help of OECD.ai data.

The country comparisons originate from the studies that were examined in section 2 of this paper with regard to their suitability for describing the research field of AI. From all studies examined for their methodological approach in section 2, the resulting country comparisons are presented in this section. Two studies are not included, hower: The results of the OECD study from 2020 are based on data from 2018 and therefore have historical value, but are less suitable for describing the current situation. And the CSET study is purely a methodological study ("Identifying AI Research") that does not make its own country comparisons. However, as the CSET-keyword list is the basis for the AI Index Reports, their work in presented in this section as well.

5.1 Liu, Shapira and Yue 2021

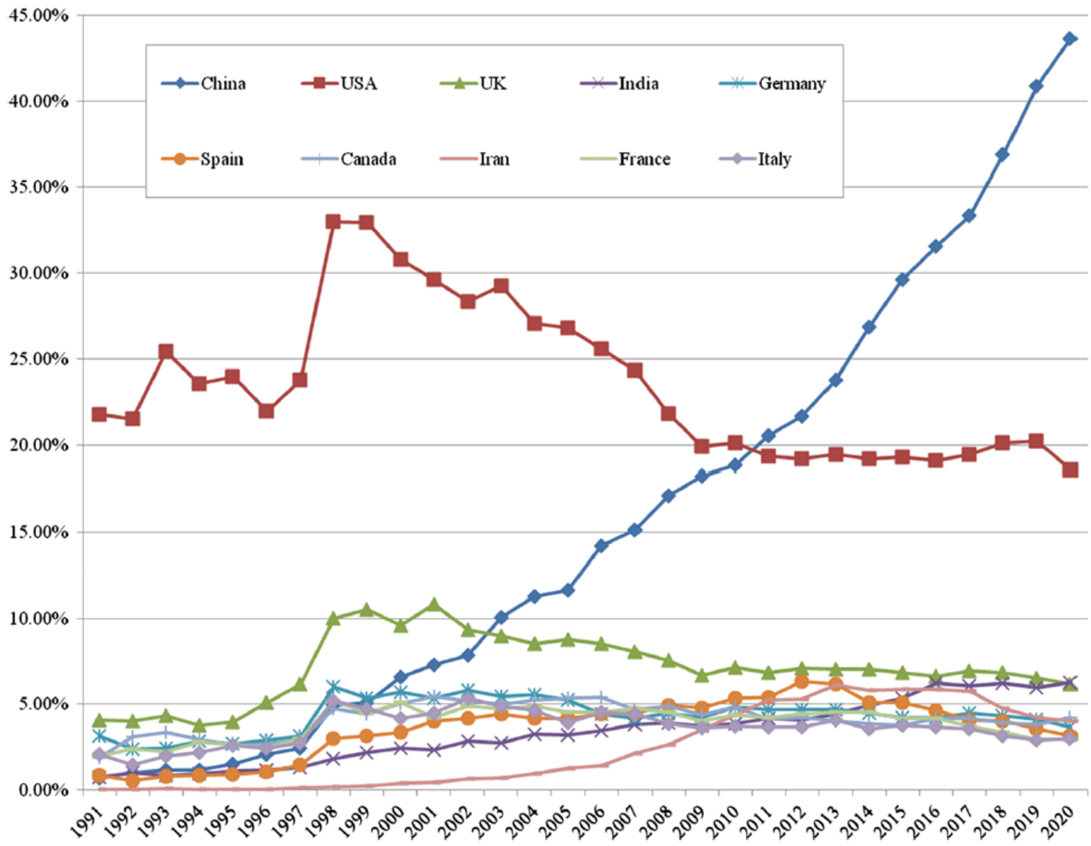
Liu, Shapira and Yue (2021) apply their methodology to come up with a series of country comparisons. Two of these will be presented here, firstly the development of the share of global AI research from 1991 to 2020 (Figure 14) and secondly the development of citation rates since 2000 (Table 10).

The chart shows that China overtook the USA in terms of the number of published AI papers in 2011 and is the undisputed leader in 2020 with more than twice as many AI articles. If we look at the relevance of the published articles, a different picture emerges however.

As Table 10 shows, China has also caught up in terms of citations in recent years, although the US sill ranking on place one in the most recent period under review (2015-2019). Despite the enormous increase in research papers, China was therefore unable to keep up with the relevance of these papers.

Iran (7.7 percentage points) and Italy (3.8 percentage points) stand out with strong increases between the first phase under review and the most recent phase.

Figure 14: Development of the share of AI articles in the top 10 countries between 1991 and 2020 according to Liu, Shapira and Yue 2021



Source: Liu, Sharpira and Yue 2021, p. 3178, Basis: WoS (SCI-E and SSCI)

Table 10: Country shares by citations according to Liu, Shapira and Yue 2021

Table 7 Country share of top 10% of the most cited artificial intelligence articles worldwide, 2000–2019

	2000–2004	2005–2009	2010–2014	2015–2019
All articles, worldwide (× 1000)	36.0	58.9	102.8	195.8
In worldwide top 10% most-cited	%	%	%	%
US	15.2	15.3	15.4	13.0
UK	12.4	13.4	14.0	12.6
Canada	9.8	12.2	12.9	12.2
Italy	8.0	9.2	10.2	11.8
Iran	4.0	6.0	7.8	11.7
Germany	10.6	14.0	14.5	11.6
China	9.3	10.2	11.6	11.5
France	10.5	11.8	11.6	10.9
Spain	7.1	7.8	9.2	9.5
India	7.4	8.0	8.8	8.5

Source: Liu, Shapira and Yue 2021, p. 3180

5.2 Gao and Ding 2022

The analysis by Gao and Ding 2022 was important for the classification of the research field of AI, particularly with regard to the emergence of new topics. Their analysis does not focus on country comparisons. However, they identify a top 15 list of companies that own AI patents, which shows that US companies are clearly leading in this area (see Table 11).

Table 11: Top 15 patent holders in the field of AI between 2000 and 2019 according to Gao and Ding 2022

Table 8 Top 15 ranked assignees

Company	Number	Burst	Country	Company	Number	Burst	Country
IBM	1,265	87.97	USA	INTEL	243	14.17	USA
MICROSOFT	607	83.6	USA	AMAZON	162	28.04	USA
GOOGLE	434	36.22	USA	NEC	154	7.65	Japan
BAIDU	397	35.3	China	QUALCOMM	136	8.91	USA
FANUC	292	7.59	Japan	APPLE	129	12.46	USA
SAMSUNG	288	3.91	Korea	FUJITSU	124	3.77	Japan
FACEBOOK	263	28.35	USA	SIEMENS	114	5.47	Germany
				CISCO	111	15.17	USA

Source: Gao and Ding 2022, p. 12995, "Burst" values are calculated using the burst detection technique. A burst indicates abrupt changes of events (p. 12978).

However, Gao and Ding put the dominance of US companies in AI patents into perspective by pointing out that in China it is not the companies that apply for patents, but predominantly the universities and research institutions.

The patent figures were determined on the basis of an expanded definition of AI, which in addition to "artificial intelligence" and "machine learning" also includes fields of application such as "natural language processing", "smart robot", "video recognition" and "gesture control" (Gao and Ding 2022, p. 12976).

5.3 AI Index Report 2023 and 2024

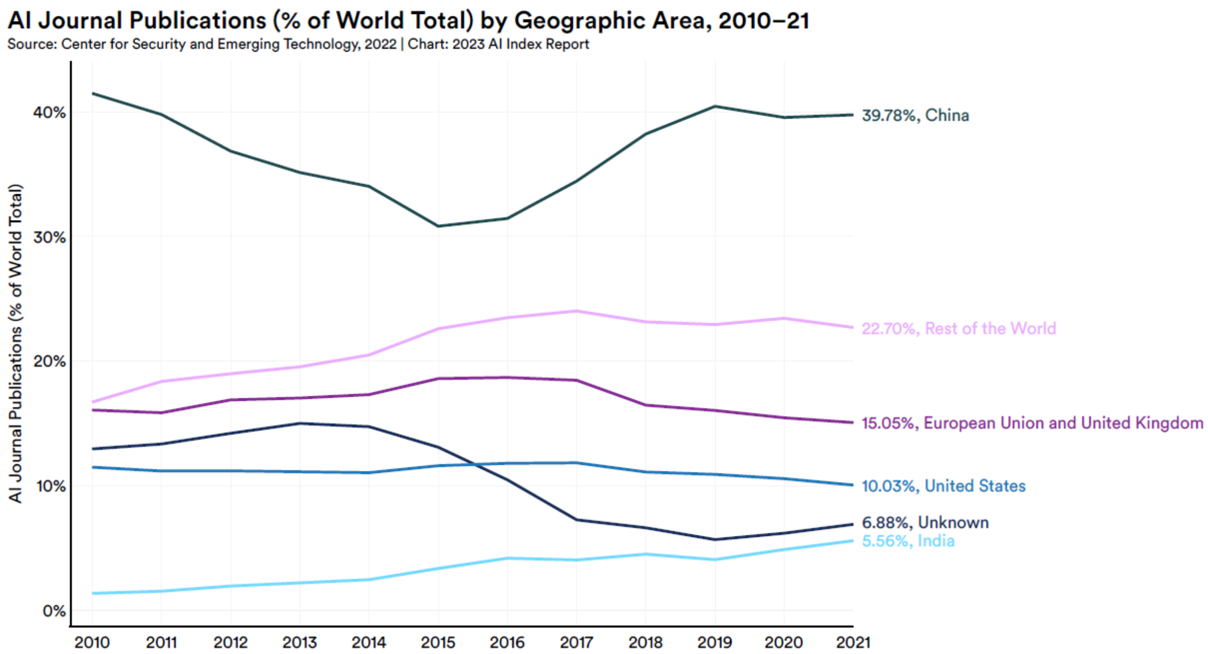
An important source for the country comparison is the AI Index Report from Stanford University, which has been published annually since 2017. For bibliometric and patent analyses, the AI Index Report uses the keyword list and the corpus of the Center for Security and Emerging Technology (CSET), which was analyzed in detail in section 2.

The 2023 AI Index Report (which presents results from 2022, which in turn are based on figures from 2020-21) determines the strength of AI research in China, the USA and Europe based on both the absolute number of research articles and citations. Interesting differences emerge depending on whether journals, conference papers or pre-print repositories (ArXiv, Semantic Scholar) are considered.

In the more recent 2024 edition of the report, the publication and citation figures broken down by country are missing, so the 2023 report is used. The 2024 report again contains interesting patent analyses, which are presented at the end of this section.

According to the AI Index Report 2023, China ranks first in terms of the absolute number of AI journal articles, well ahead of Europe and the United States (Figure 15).

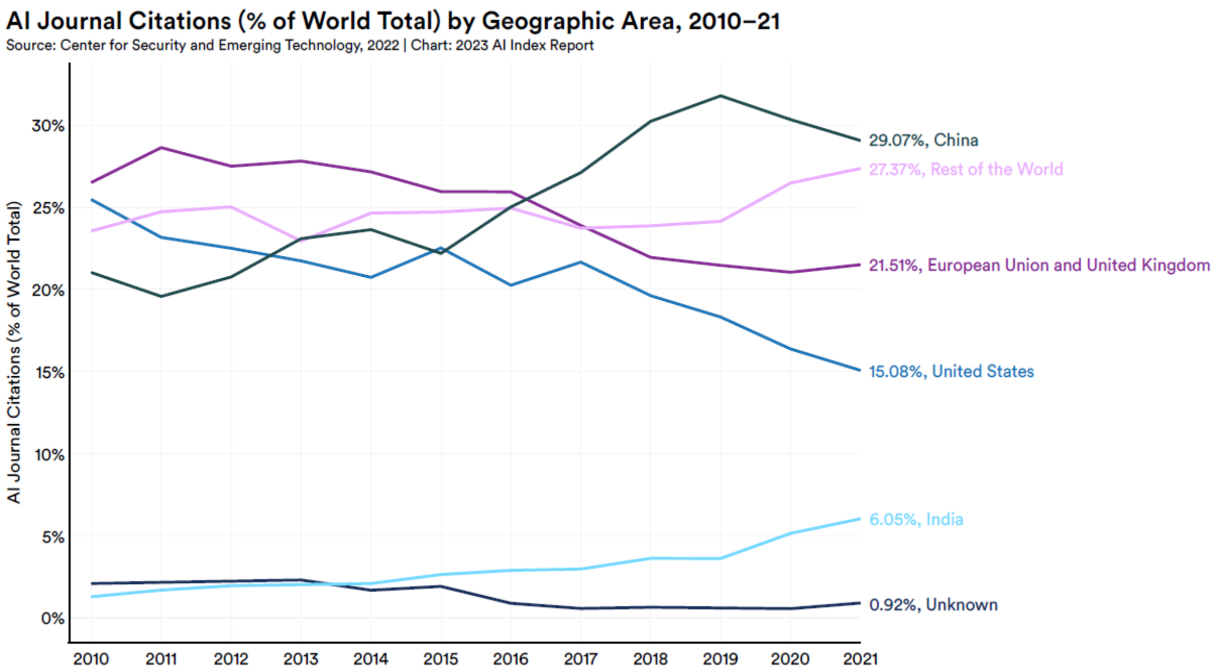
Figure 15: Country shares of global AI publications between 2010 and 2021 according to the AI Index Report 2023



Source: AI Index Report 2023, p. 34

In terms of citations, China has been ahead of Europe and the USA since 2016, according to the AI Index Report (see Figure 16).

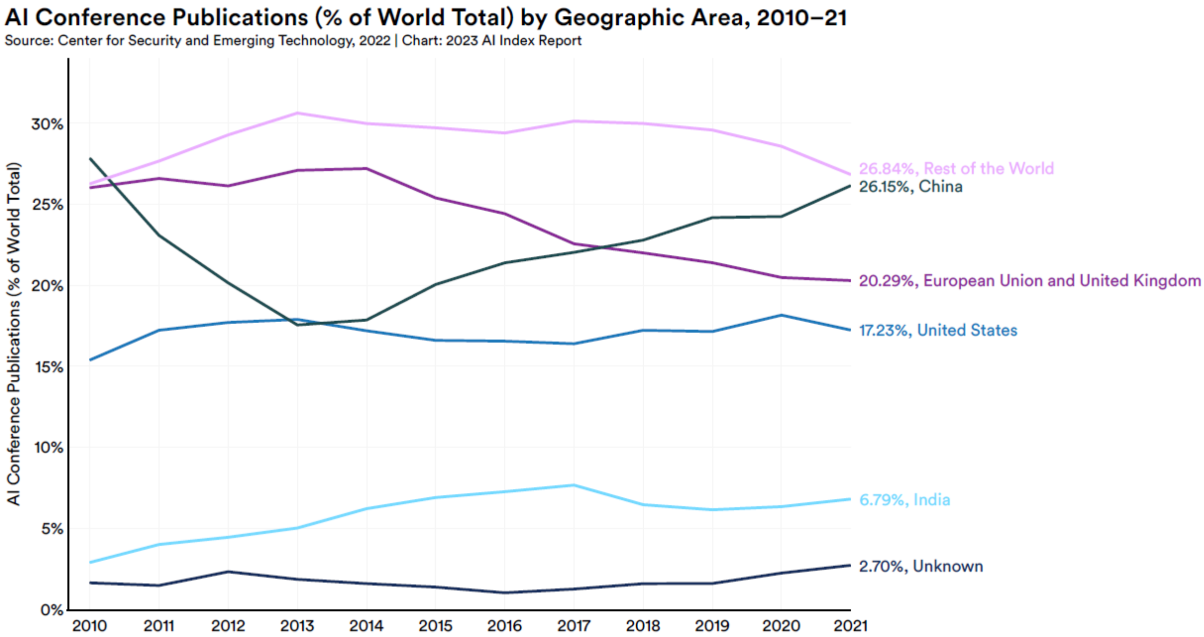
Figure 16: Country shares of global citations of AI publications between 2010 and 2021 according to the AI Index Report 2023



Source: AI Index Report 2023, p. 35

If we only look at conference publications, i.e. publications that are presented at scientific conferences and are published more quickly than journal articles, the country ranking is the same according to the AI Index Report: China is again ahead of the USA, but the gap between the two countries is smaller than for journal publications (see Figure 17). Interestingly, the EU countries and the UK are still ahead of the USA in this statistic (and also in terms of the absolute number of publications).

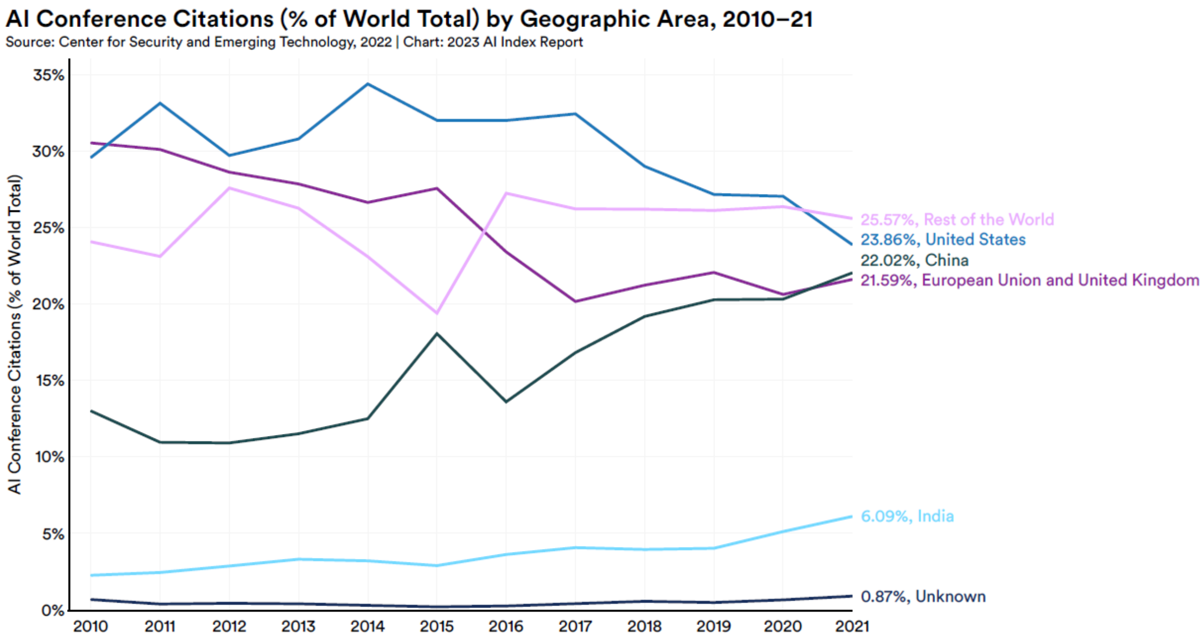
Figure 17: Country shares of global AI conference publications between 2010 and 2021 according to the AI Index Report 2023



Source: AI Index Report 2023, p. 37

The situation is different for citations of conference publications (see Figure 18). Here, the USA was just ahead of China in 2021 (23.86%, USA to 22.02%, China).

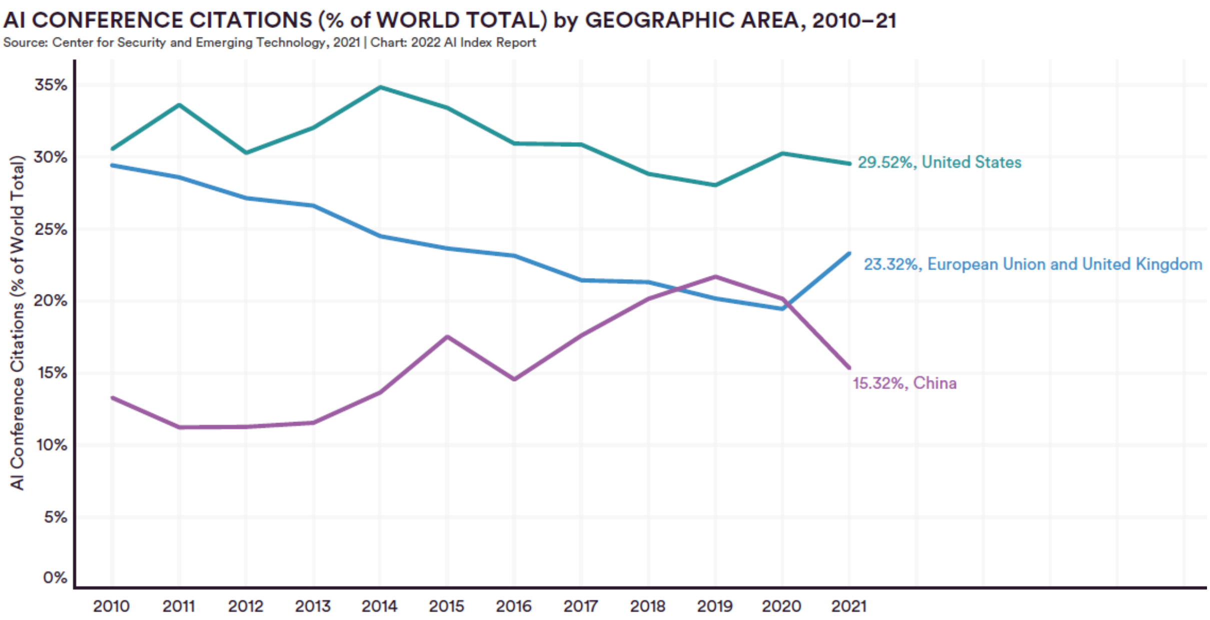
Figure 18: Country shares of global citations of AI conference publications between 2010 and 2021 according to the AI Index Report 2023



Source: AI Index Report 2023, p. 39

Interestingly, the previous year's edition of the AI Index Report 2022 showed values that were much further apart (29.52%, USA to 15.32%, China, see Figure 19). This difference is not addressed in the text of the 2023 report, meaning that the (methodological or actual) reasons for the rapid catch-up process within just one year remain unclear.

Figure 19: Country shares of global citations of AI conference publications between 2010 and 2021 according to the AI Index Report 2022

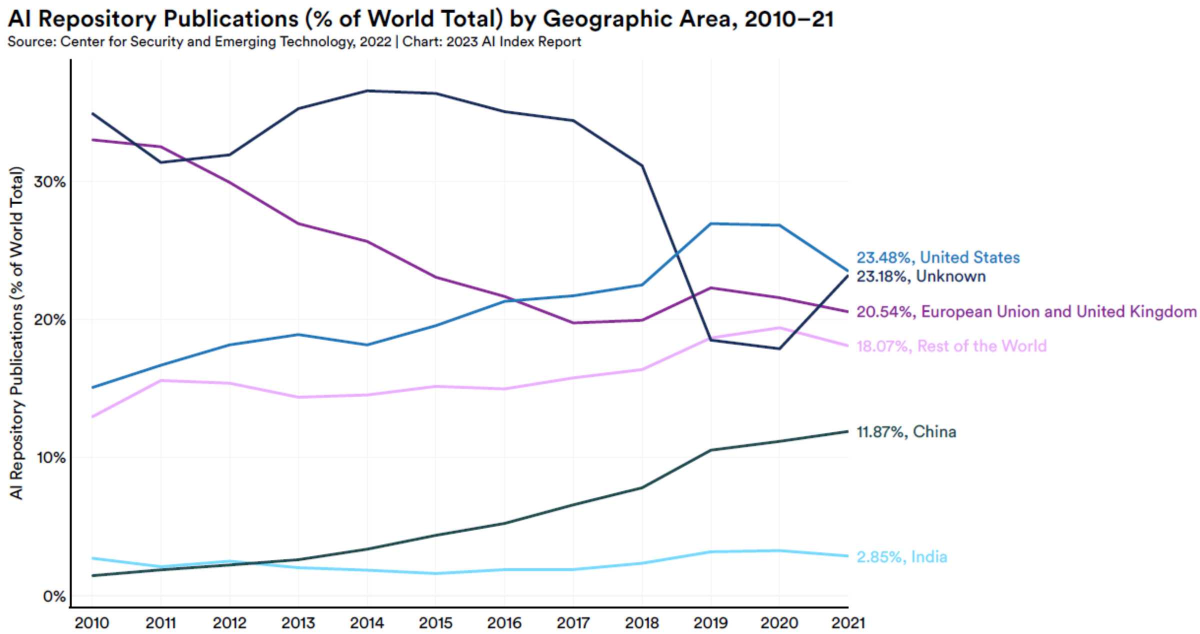


Source: AI Index Report 2022, p. 31

According to analysis of the AI Index Report 2023, the USA is still far ahead in terms of the proportion and citations of articles published on AI community platforms (repositories). These articles are preprints, i.e. pre-peer-reviewed papers. The AI Index Report describes the repositories as follows: "[AI repositories have] become a popular way for AI researchers to disseminate their work outside traditional avenues for publication. These repositories allow researchers to share their findings before submitting them to journals and conferences, thereby accelerating the cycle of information discovery. The number of AI repository publications grew almost 27 times in the past 12 years" (AI Index Report 2023, p. 40).

Of all 2021 publications in AI community platforms, such as ArXiv, 23.48% are from American scientists and 11.87% from Chinese scientists (see Figure 20).

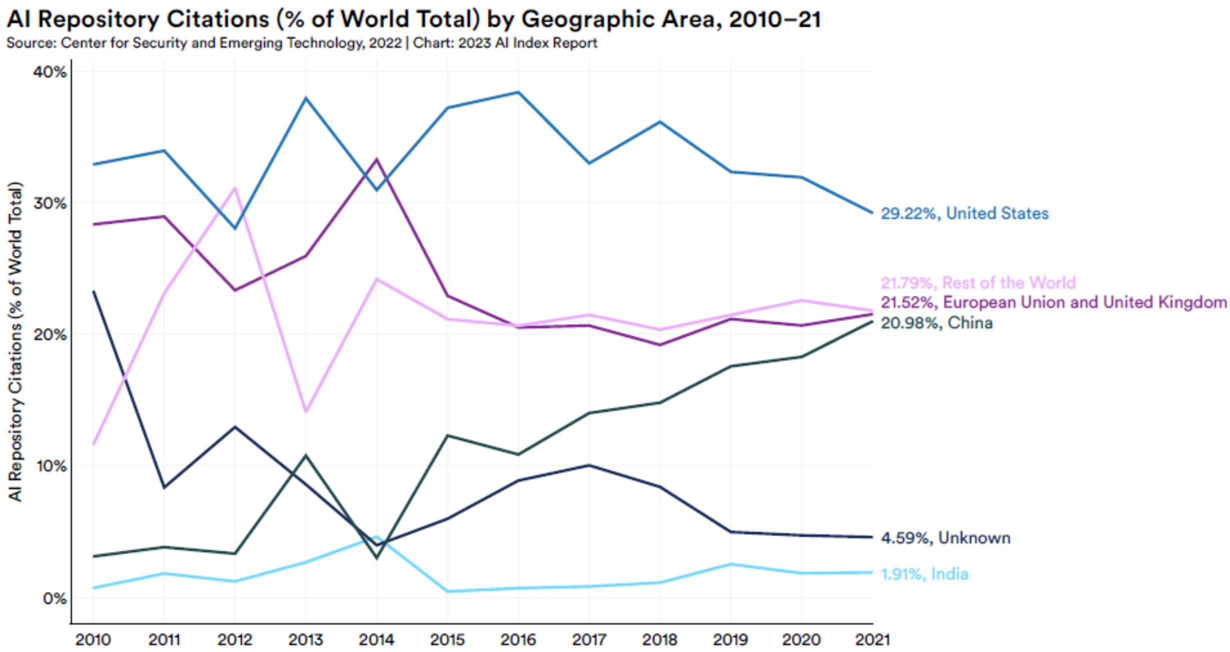
Figure 20: Country shares of AI articles published in AI repositories between 2010 and 2021 according to the AI Index Report 2023



Source: AI Index Report 2023, p. 42.

In terms of citations of articles in repositories, the USA also has a lead over China (see Figure 21).

Figure 21: Country shares of citations of AI articles in AI repositories between 2010 and 2021 according to the AI Index Report 2023



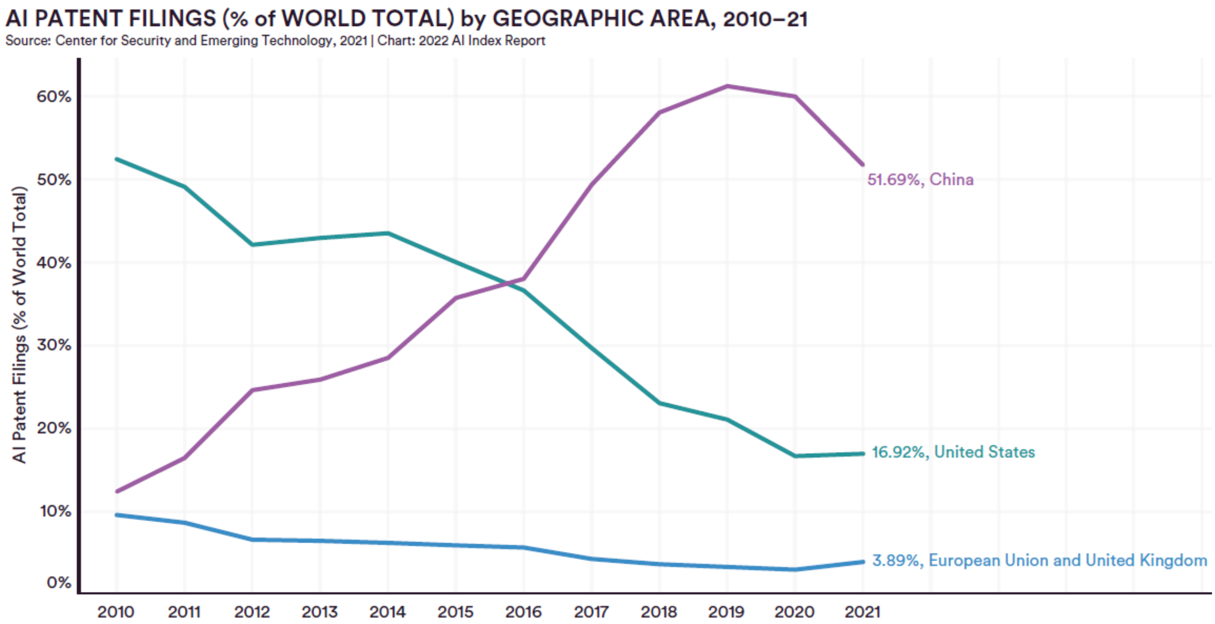
Source: AI Index Report 2023, p. 43.

The following findings emerge from the summary:

- China is ahead of the USA in terms of the number of traditional publications, i.e. journal articles and conference publications. Chinese articles are also cited much more frequently here than American ones.
- If we look at more current AI work, the picture changes: Researchers working at US institutions clearly lead the field when it comes to AI articles published in repositories and thus reflecting current developments. This is also the case for citations of these articles. However, China has also caught up in this area in recent years. China's ascending line in Figure 21 could mean that only a few, but very relevant research papers have been published there in recent years. Nevertheless, the American research contributions are currently more relevant for the international AI community than the Chinese (29.22 USA compared to 20.98 China, see Figure 21).
- In summary, it can be said that China is now ahead of all other nations in the classic AI research areas, but is lagging behind in the newer AI developments, which are determined by ML models and LLMs. The figures generally show a high level of research dynamism in the countries and suggest a more differentiated view of the research field.

Another interesting result of the AI Index Report is the development of AI-related patents. Here, too, China has now taken over the global leadership role based on the number of patents granted and their global share (see Figure 22).

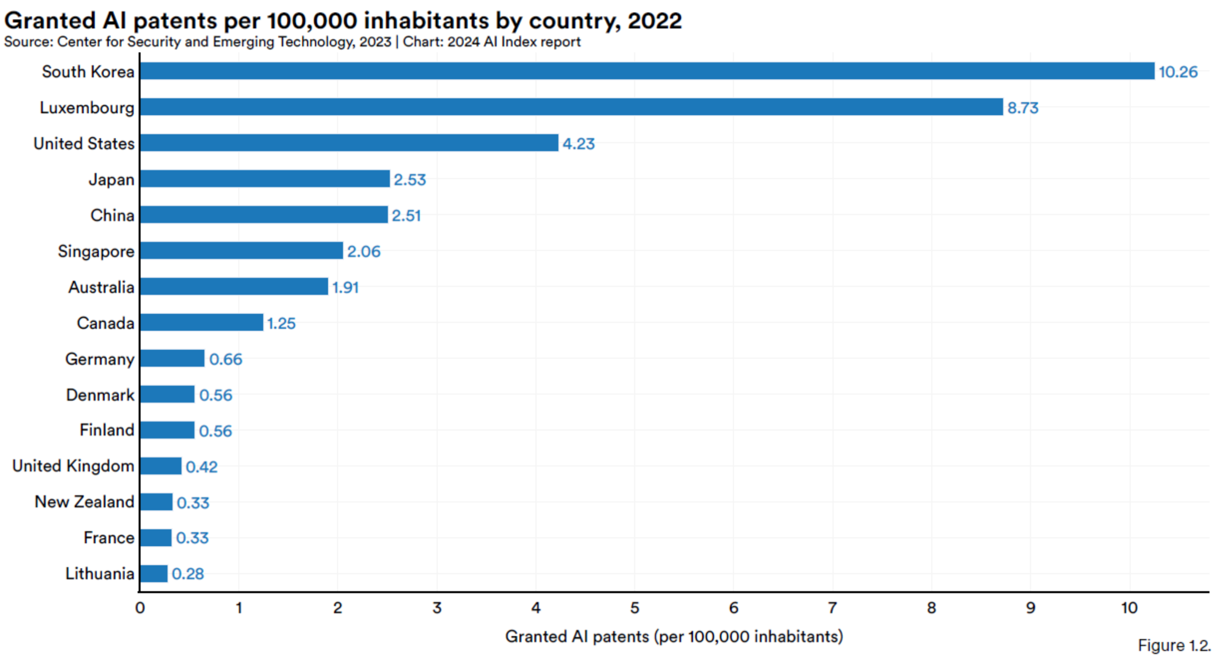
Figure 22: AI patents granted by country between 2010 and 2021 according to the AI Index Report 2024



Source: AI Index Report 2024, p. 16

However, if the number of AI patents granted is related to the size of the population, a different picture emerges (see Figure 23). This clearly shows the size effect that must generally be taken into account when considering China's research and innovation strength. However, the fact that Luxembourg is in second place in these statistics shows that standardization according to population size also has its limitations.

Figure 23: Patents granted by population size, 2022



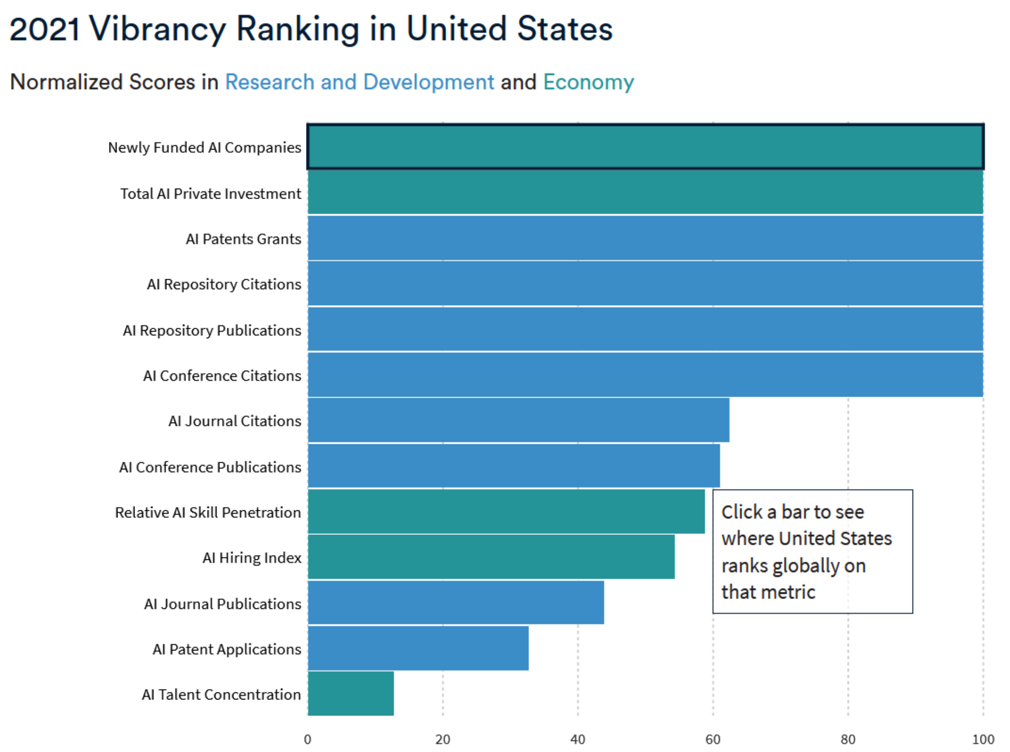
Source: AI Index Report 2024, p. 17

In addition to bibliometrics and patent analysis, the AI Index Report 2023 attempted to capture innovation activity in the field of AI using further indicators. These indicators were as follows:

- Total AI Private Investment,
- Newly funded AI companies,
- AI Hiring Index (LinkedIn AI job postings normalized to all LinkedIn job postings),
- AI Talent Concentration (LinkedIn profiles with AI reference normalized to all LinkedIn profiles of a country),
- Relative AI Skill Penetration (Linkedin job details with the additional reference to AI skills normalized to all Linkedin job details).

The performance of selected countries for these indicators is shown individually in the AI Index Report 2023 and only partially in a country comparison (see Chapter 4 "The Economy" of the AI Index Report 2023 from p. 168). In the associated web tool "AI Vibrancy Tool", which was online at https://aiindex.stanford.edu/vibrancy until summer 2024, it was possible to create country comparisons with an entire set of indicators. The following two figures are screenshots from the AI Vibrancy Tool and show the situation for the USA and China in 2021.

Figure 24: "Vibrancy" of the USA as a location for innovation according to the AI Index Report 2023



Source: Global AI Vibrancy Tool https://aiindex.stanford.edu/vibrancy/, based on various sources presented in the AI Index Report 2023 from p. 168.

Figure 25: "Vibrancy" of the innovation location China according to the AI Index Report 2023

Source: Global AI Vibrancy Tool https://aiindex.stanford.edu/vibrancy/, based on various sources presented in the AI Index Report 2023 from p. 168

The economic indicators (green bars) show a clear lead for the USA. This applies in particular to the absolute number of AI start-ups per year and the total amount of private AI investments in 2021. However, the USA is also ahead of China in terms of labor market-related variables (qualifications, job advertisements, applicant profiles).

However, China leads the ranking in terms of research indicators (blue bars), a finding described in detail above.

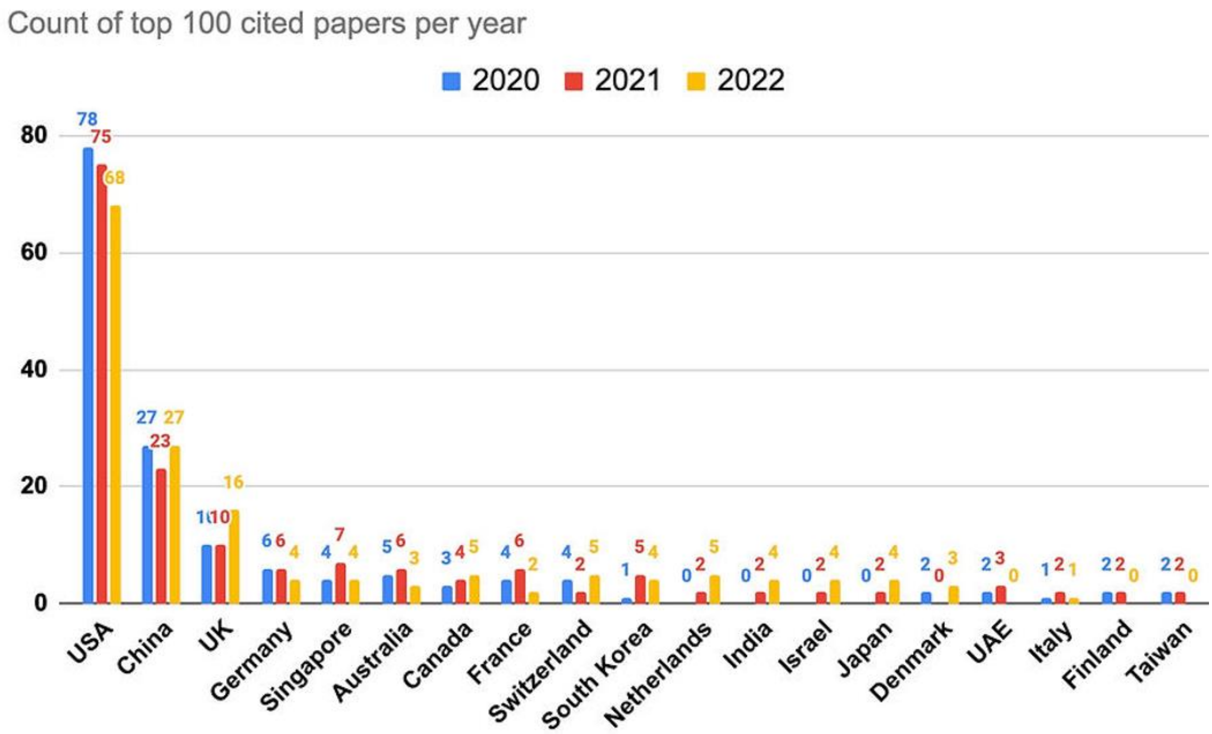
5.4 Zeta Alpha 2023

Another source for determining the research strength of different countries in the field of AI is the analysis by Zeta Alpha from 2023. Zeta Alpha analyzed the 100 most cited AI articles of 2022, based on AI articles published on the community platform ArXiv but also includes articles published on the Semantic Scholar platform.[16]

The Zeta Alpha analysis analyzes the period from 2020 to 2022 and shows a clear lead for the USA (see Figure 26). It is not possible to determine whether the lead has only recently increased or has always been greater due to the different survey method.

[16] The focus on community platforms allows a comparison with the results of the AI Index Report from Stanford University (see above). The report analyzed repository citations between 2010 and 2021 and determined a share of 29.22% for the USA and 20.98% for China. In the Zeta Alpha analysis, the distance between the US and China is much greater, asFigure 26shows.

Figure 26: The 100 most cited AI articles in AI repositories for 2020-2022 by country according to Zeta Alpha 2023



Source: Zeta Alpha 2023, p. 1

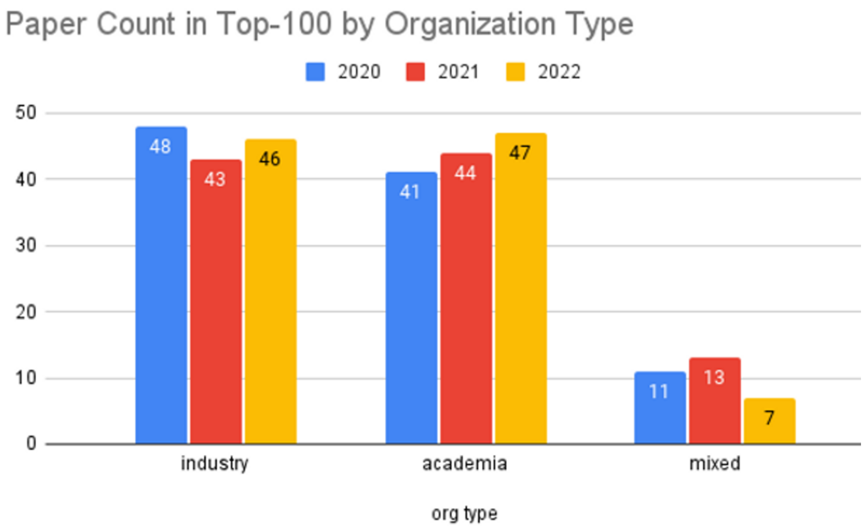
Of the most cited articles published on AI platforms in 2022, 68 were written by American scientists and 27 by Chinese scientists. The articles were written in the same year (plus January and February 2023), according to Zeta Alpha. Compared to 2020, the number of American contributions has decreased (2020: 78) and the number of Chinese contributions has remained the same (2020: 27). According to Zeta Alpha, the count does not include the nationalities of researchers, but rather the country in which their research organization is located.[17]

Analyzing the list of the top 100 cited articles in terms of the topics covered, it is evident that many of the articles deal with large language models (LLMs) and generative AI. These sub-areas of artificial intelligence research have been the subject of much discussion in the research community since the publication of ChatGPT in fall 2022. China apparently did not recognize this trend early on; observers claim that China was taken by surprise by this development ("ChatGPT took China completely by surprise", see Sharma 2023). Chinese researchers are now trying to catch up in the area of large language models. According to official figures, there were already 130 Chinese LLMs in February 2024 (Sharma 2024). According to a researcher at Tsinghua University, these are at the technical level of ChatGPT 3.5 (Dou Dejing cited in Sharma 2024). It is unclear how quickly China can catch up in this area (see White 2024). High costs, the lack of graphics chips due to the US embargo and the strict censorship of content are cited as barriers.

Another interesting result of the analysis of the top 100 cited articles by Zeta Alpha is the finding that around half of the analyzed articles are written by AI experts who are employed by companies (see Figure 27). These companies include Google, Meta, Microsoft, DeepMind, OpenAI and NVIDIA.

[17] personal communication with Jakub Zavrel from Zeta Alpha on December 1, 2023.

Figure 27: The 100 most cited AI articles in AI repositories for 2020-2022 by organization type according to Zeta Alpha 2023



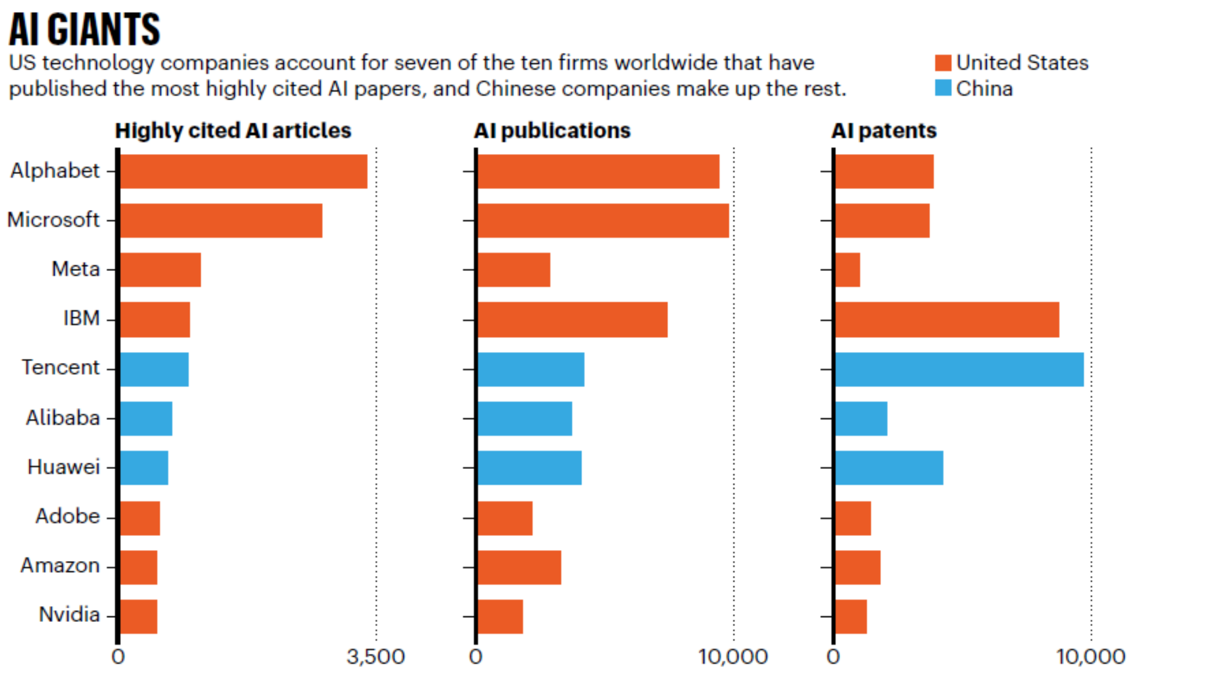
Source: Zeta Alpha 2023

The background to the strength of companies in AI research is the need to use large computing capacities and access large amounts of data in order to train large language models. US tech companies such as Google, Meta, Microsoft and Amazon therefore have an advantage in the development of complex AI models.

An Elsevier analysis commissioned by the Japanese business newspaper Nikkei in 2022 confirms this statement and specifies the situation in China in particular: According to this analysis, six out of ten of the most cited AI research articles in 2021 were written by researchers working for American tech companies, four were from the Chinese companies Tencent, Alibaba, Huawei and State Grid Corporation of China (Fukuoka; Tabeta; Oikawa 2023). No further details are provided on the methodology of the Elsevier evaluation, but the fields of application on which the Chinese companies are focusing on were described: "As a government-owned power distributor, State Grid also boasts one of the best AI research arms among Chinese corporations. This is made possible by the big data collected from hundreds of millions of smart meters. State Grid Corp. is developing technology to predict power demand and to detect problems in the electrical grid. Baidu, which provides China's leading search engine, came in at 11th place in both the quantity and quality of AI research. The tech giant is rolling out a fleet of fully self-driving cabs" (Fukuoka; Tabeta; Oikawa 2023).

Calculations by the "Private-sector AI-Related Activity Tracker" (https://parat.eto.tech), a data platform operated by CSET, come to a very similar conclusion for the year 2023: US companies clearly lead the field of the most cited articles from the corporate environment with seven companies in the top 10 (see Figure 28). In terms of patents, however, Chinese companies (Tencent and Huawei) take the lead in this analysis.

Figure 28: USA vs. China for key company-related AI indicators

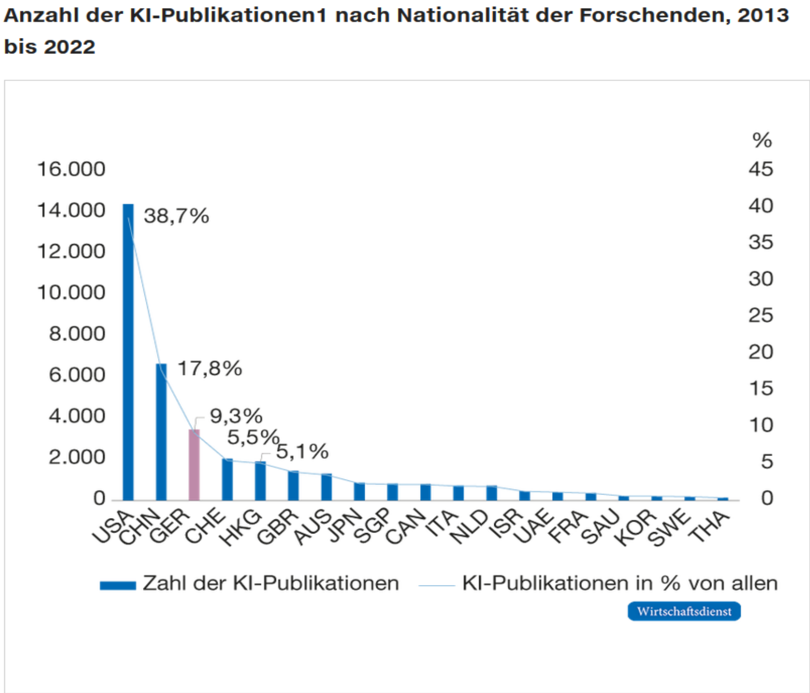


Source: Gibney 2024 based on data from PARAT/ETO/CSET

5.5 Würzburg Group 2023

The work of the Würzburg Group was particularly relevant in the previous section with regard to the subdivision of AI research areas. It was said that it would in principle be possible to create differentiated country-specific research profiles using the data from the Würzburg Group. However, such an evaluation currently does not exist. However, a country comparison was carried out across all AI segments, including Natural Language Processing, Machine Learning, Problem Solving, Cognitive AI, Knowledge Representation, Uncertainty, Computer Vision, Robotics. This analysis was presented by Volker Brühl 2023 in the journal Wirtschaftsdienst. The evaluation refers to the number of all AI publications in the dlpd literature database between 2013 and 2022 and sees the USA clearly in the lead with 38.7% of all articles published in this period (see Figure 29).

Figure 29: Country comparison of AI publications between 2013 and 2022 according to the Würzburg Group



Source: Brühl 2023 based on the web tool of the Würzburg Group, https://airankings.professor-x.de (CHE=Switzerland, HKG=Hong Kong, SGP=Singapore, SAU=Saudi Arabia, THA=Thailand)

Interestingly, the ranking puts Germany in third place, a result that differs significantly from other studies such as those by Liu, Shapira and Yue 2021 or the AI Index Report 2023. One explanation for this could be found in the text corpus on which the analysis is based on. It is possible that articles by German researchers are overrepresented in the dblp. It is also unclear how large the total number of articles is in the selected period; although the dblp lists around 200,000 researchers as authors of articles, many of them published more than one article.

Another reason for Germany's good performance could be that Brühl uses cumulative values for the years 2013 to 2022, a difference to many other studies. But even this cannot fully explain Germany's position in the ranking.[18]

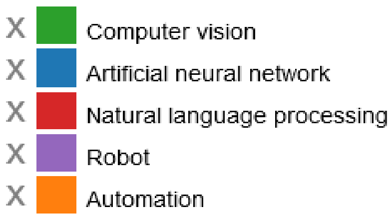
5.6 OECD.AI country comparisons

The OECD web tool "Live Data" (https://oecd.ai) uses two different databases to determine the country-specific AI research strength, namely Scopus and OpenAlex. As shown in section 2.8, the ranking for 2023 is as follows: China, EU27, USA, India, UK, Germany, Italy and Japan. This ranking is based on the shares of total publications in the field of AI according to Openalex.org. Using Scopus as a database and also the citations show a similar order.

An interesting selection option in the OECD web tool is the menu item "Top countries by AI research application area". Five AI application areas are offered (see Figure 30), with "Robot" and "Automation" referring to specific application areas, while "Computer vision", "Artificial neural network" and "Natural language processing" could be assigned to both basic research and applications.

[18] A comparative analysis via Openalex.org puts Germany at place five in the ranking, presenting the following order: USA, China, India, UK, Germany, France. Switzerland in the Openalex-analysis only ranks 17th. This case clearly shows how important the selected time period and the corpus used are in addition to a suitable keyword list.

Figure 30: "Research application areas" of the OECD web tool OECD.ai "Live Data"

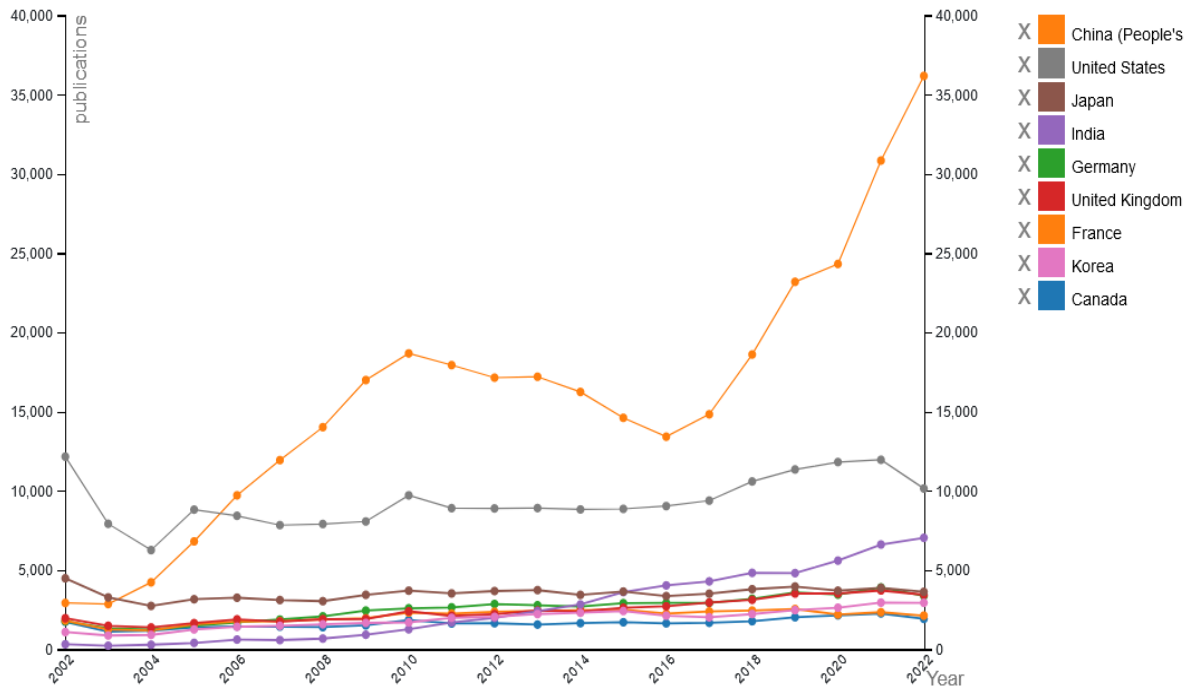


Source: Screenshot OECD.ai, "Trends in AI research application areas by country"

The overall picture shows that "Computer vision" and "Artificial neural network" are the two areas in which the most AI articles have been published (approx. 100,000 publications each worldwide in 2022, see Figure 6: Trends in AI research application areas in section 2.8). Natural language processing" and "Robot" follow in third and fourth place (approx. 40,000 publications each) and "Automation" is in last place with only approx. 5,000 publications in 2022.

The following figures show the country strengths in all of the five application areas based on the number of publications in 2022. The results are presented in detail because the OECD report on AI in Germany (OECD 2024), among others, extensively refers to this evaluation.[19]

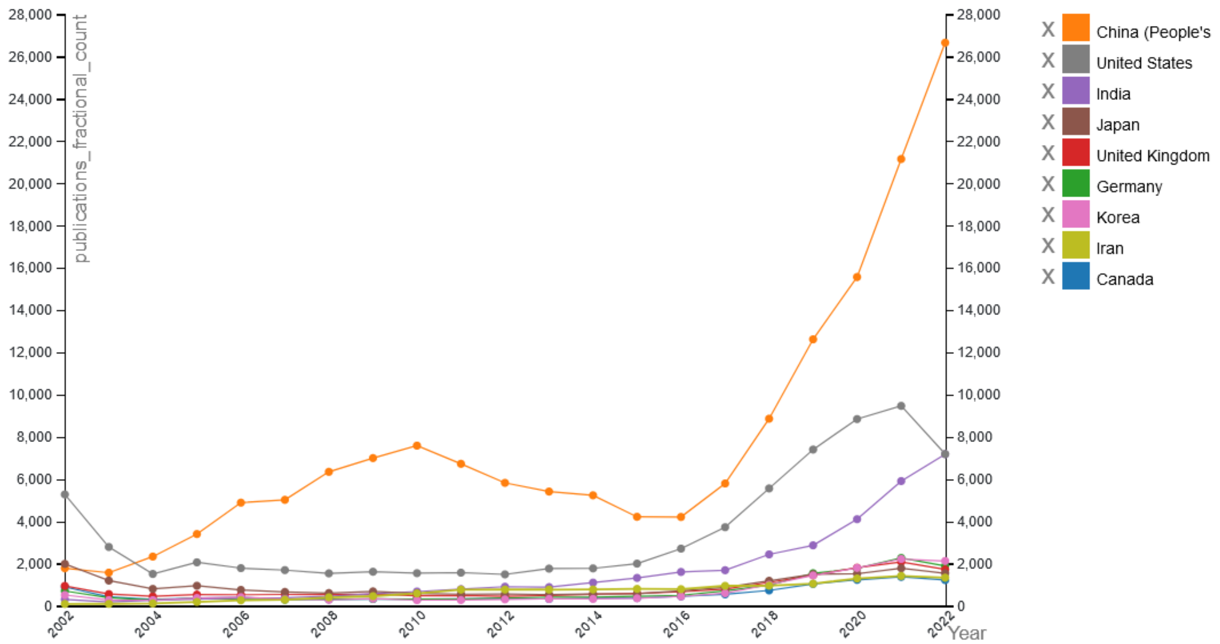
Figure 31: "Computer vision", 2002-2022 all publications



Order: China, USA, India, Japan, Germany. Source: OpenAlex via OECD.AI, retrieved on 4.10.2024.

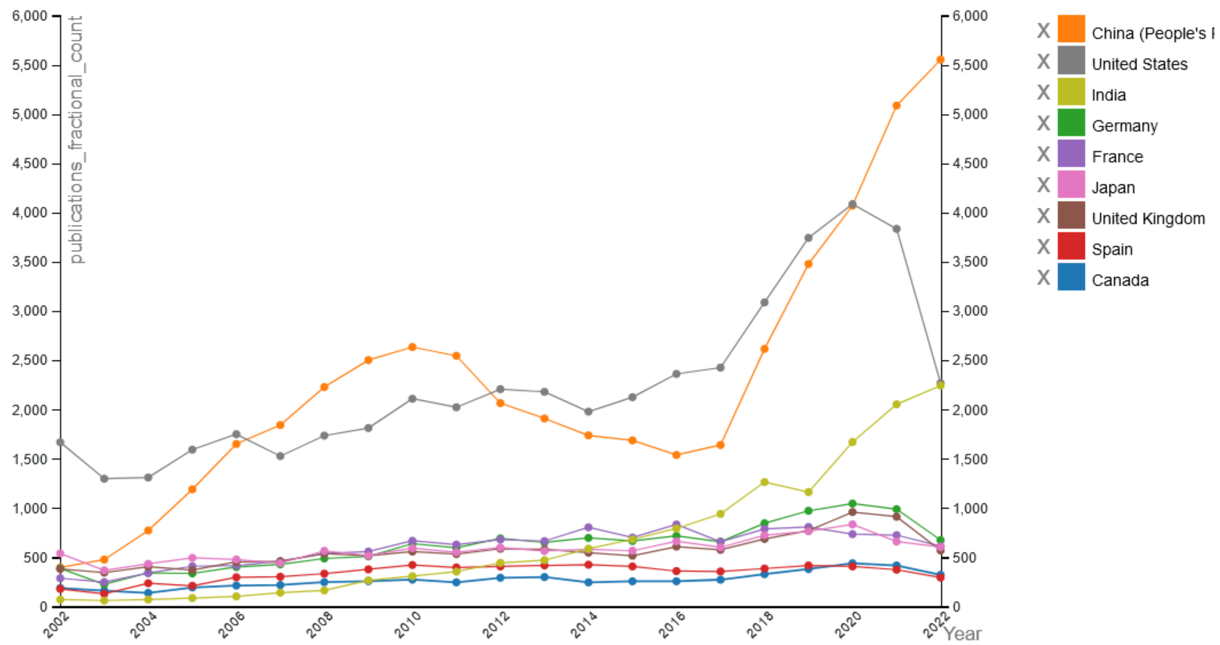
[19] In the report on AI in Germany, the AI publications are cumulated, which puts Germany in third place in the "Automation" field ahead of India (and not in fourth place as shown here).

Figure 32: "Artificial neural network", 2002-2022 all publications



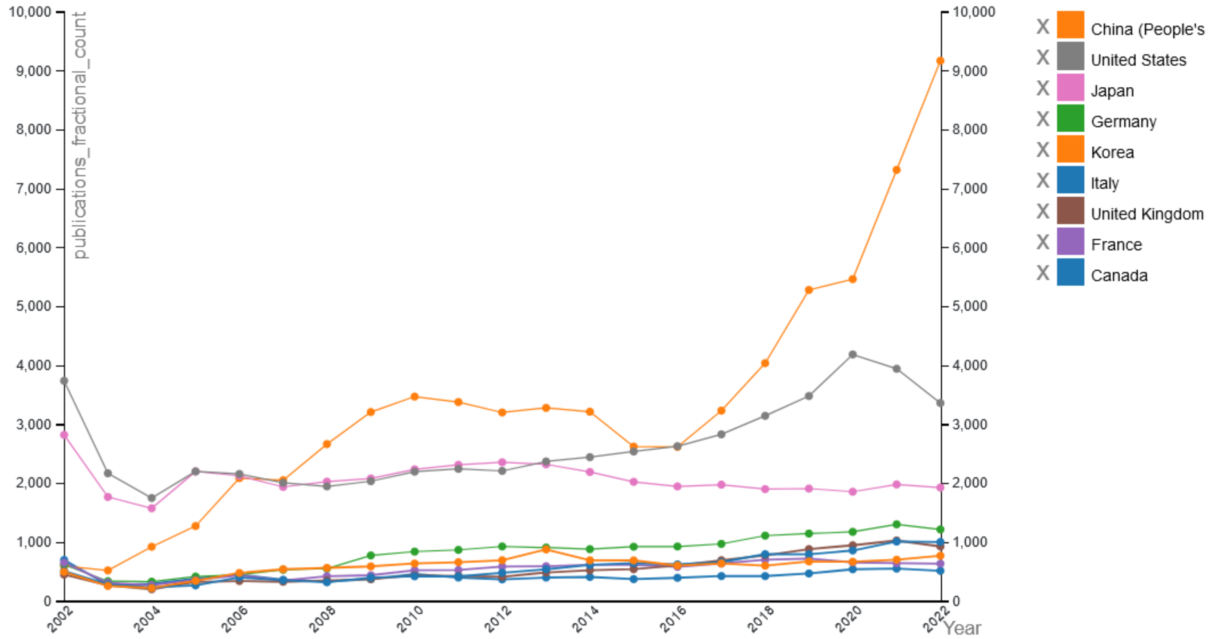
Order China, USA, India, Korea, Germany, UK. Source: OpenAlex via OECD.AI, accessed on 4.10.2024.

Figure 33: "Natural Language Processing", 2002-2022 all publications



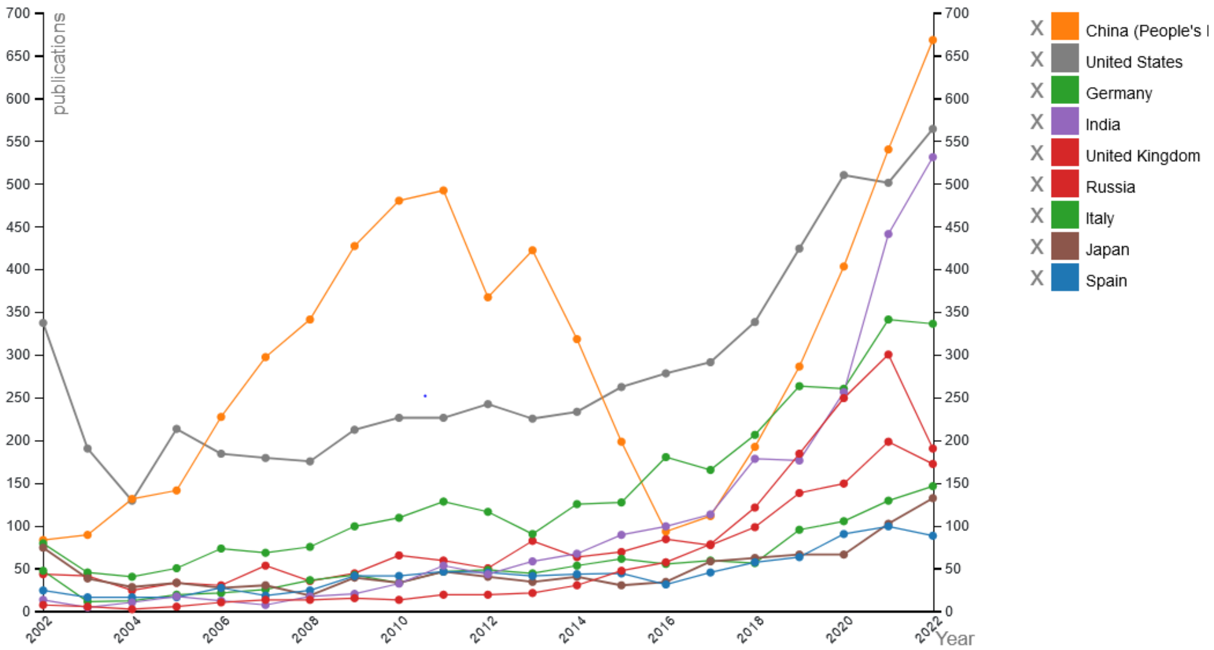
Order: China, USA, India, Germany, France. Source: OpenAlex via OECD.AI, accessed on 4.10.2024.

Figure 34: "Robot", 2002-2022 all publications



Order: China, USA, Japan, Germany, Italy, UK. Source: OpenAlex via OECD.AI, retrieved on 4.10.2024.

Figure 35: "Automation", 2002-2022 all publications



Order: China, USA, India, Germany, UK, Italy, Russia, Japan. Source: OpenAlex via OECD.AI, retrieved on 4.10.2024.

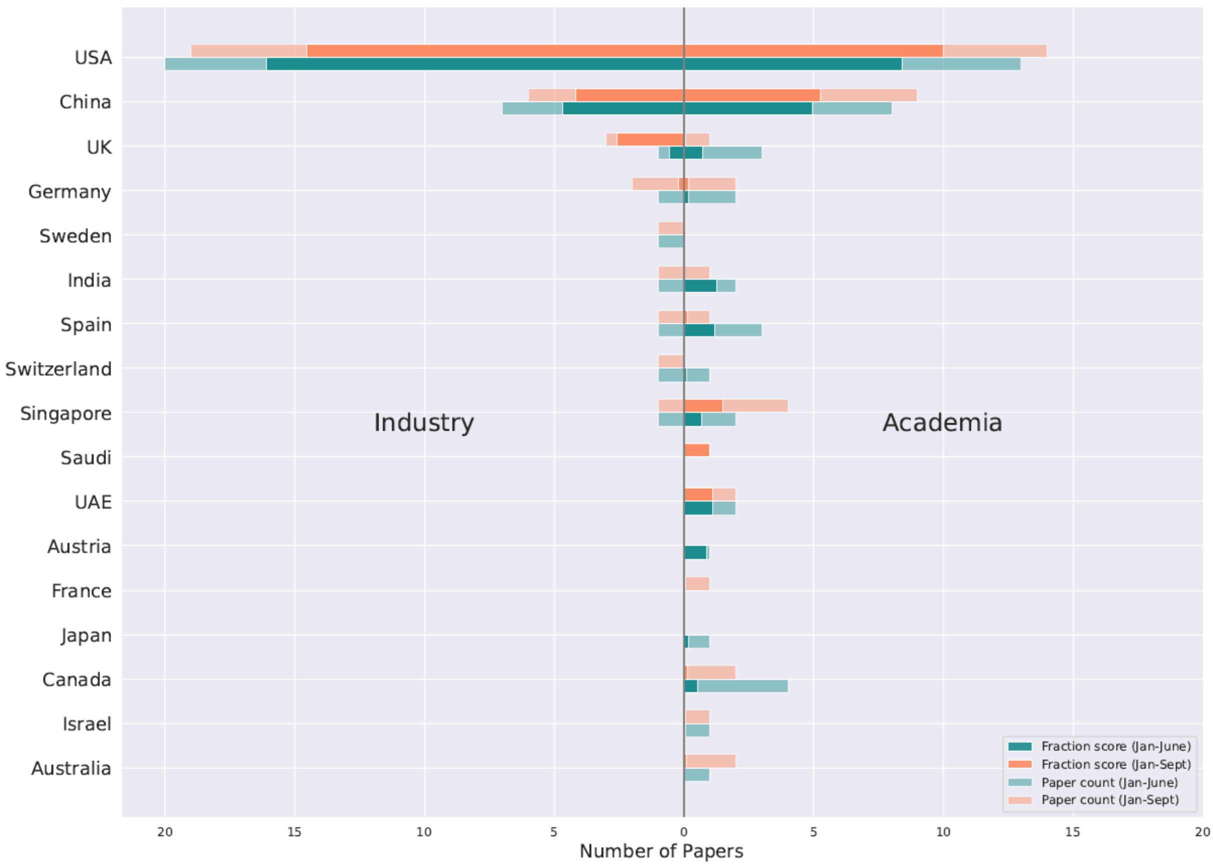
The OECD report on AI research in Germany concludes from these figures that Germany is particularly well placed in the three AI application fields of "natural language processing", "robotics" and "automation": "Germany occupies a leading position worldwide and is a leader in robotics, automation and AI research in the fields of energy and manufacturing." (OECD 2024, P. 35).

Even if the phrase "is the leader" has to be qualified (because China leads by far in all areas in terms of the number of publications, followed by the USA and India), the charts show that Germany is strong in research and innovation in the three areas mentioned and is in 4th or 5th place in a global comparison.

5.7 NLLG 2023

The analysis of the Natural Language Learning Group (NLLG) at the University of Mannheim focuses in particular on new language models. The NLLG study works with citations and analyzes the list of the 40 most-cited AI articles published in the first three quarters of 2023. Figure 36 shows the importance of industry research compared to university research in the different countries. The orange bars show the number of cited AI articles, the turquoise bars the "fraction score". This is the relative contribution of an institution to the individual articles, which is determined by the number of authors from the respective field (cf. NLLG 223, p. 14, fn 6).

Figure 36: Top 40 cited AI articles in 2023 by country and assignment to industry or university/ research according to NLLG 2023



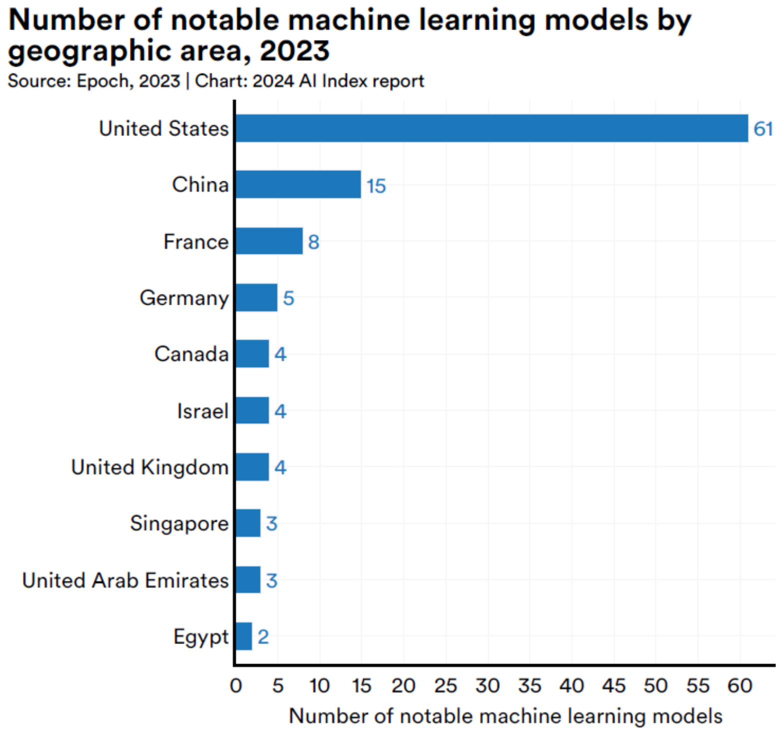
Source: NLLG 2023, p. 18

The analysis shows that in 2023, AI research was dominated by the United States of America, both in the area of corporate research and in academic research. China follows in second place, with the UK leading European research into language models, followed by Germany, Spain, Sweden and Switzerland.

5.8 Epoch AI

Epoch AI has analyzed its database of the most important ML models ("notable machine learning models") by country of origin and created the following ranking (Figure 37).

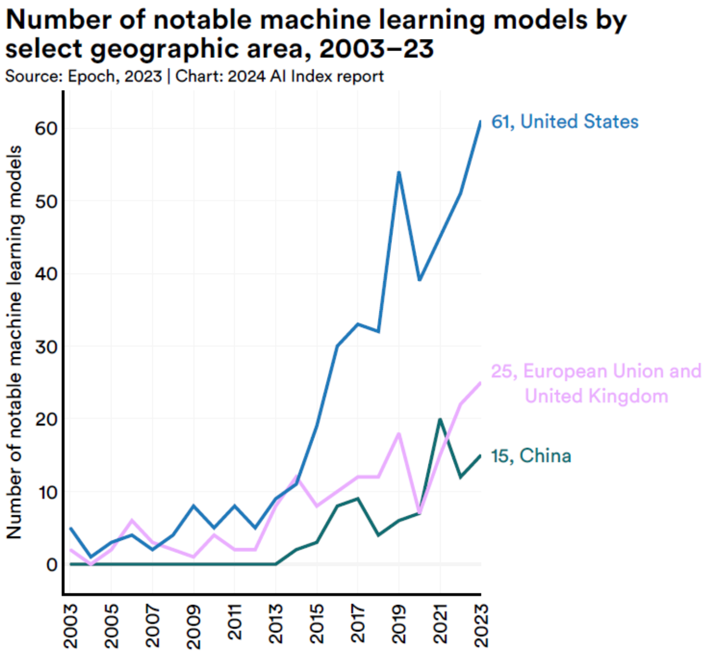
Figure 37: Number of relevant ML models by country in 2023 according to Epoch 2023



Source: AI Index Report 2024, p. 21, based on data from Epoch AI 2023

Over time, it can be seen that the era of ML models began around 2013 and that US research overtook other countries within a few years. In recent years, European countries (including the UK) have developed faster in this area than China (Figure 38). For the year 2023, Epoch AI identifies 61 relevant ML models developed in the USA. In China, there were four times fewer, namely 15. Fance and Germany follow on place 4 resp. 5.

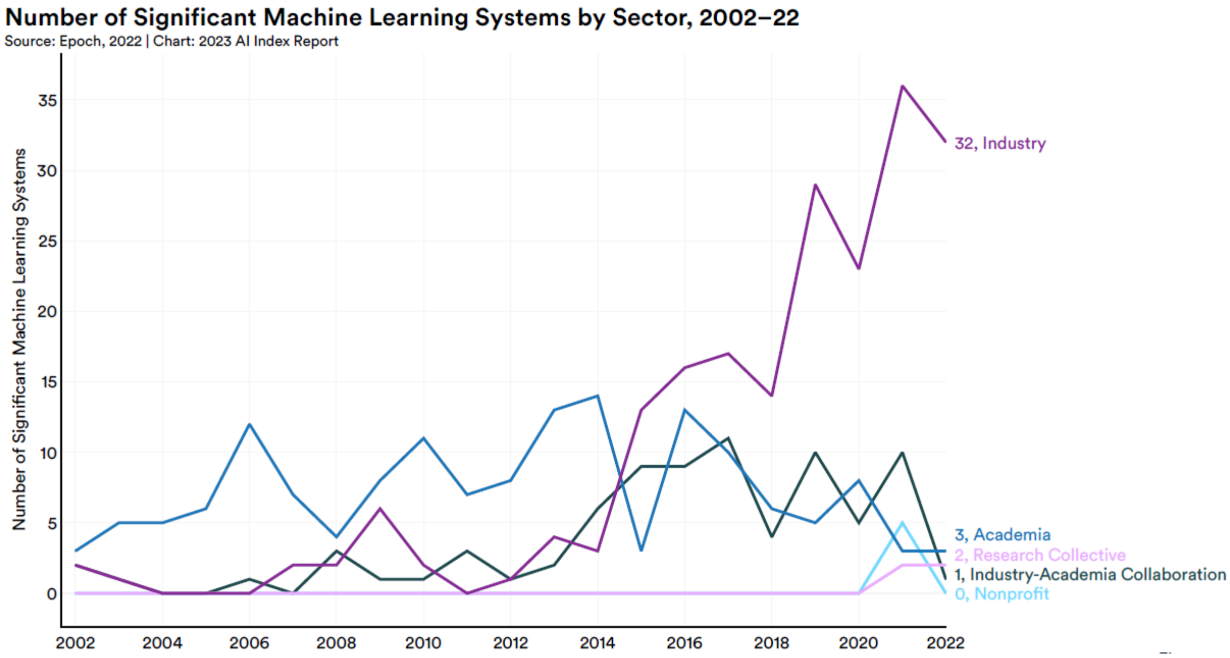
Figure 38: Development of relevant ML models by country between 2003 and 2023



Source: AI Index Report 2024, p. 21, based on Epoch AI data from 2023

Another interesting result of the Epoch AI analysis is the finding that relevant ML models and in particular large-scale ML models ("significant" or large-scale ML models) are increasingly being created by large Internet companies and industrial research in general. This is a recent trend, as academic research dominated ML models until around 2014 (Figure 39). The tech industry now dominates this field. In 2022, 32 of a total of 38 ML models described as "significant" were developed and published by companies. This shows a concentration of research power in (American) tech companies.

Figure 39: Development of LLMs by country between 2002 and 2022 according to Epoch AI



Source: Stanford University AI Index Report 2023, p. 50, based on Epoch AI data from 2022.

A more detailed country ranking is provided by two further Epoch analyses, which use cumulative figures (see Figure 40 and Figure 41).

Figure 40: LLMs by country. Development from 2017 to 2024 according to Epoch AI

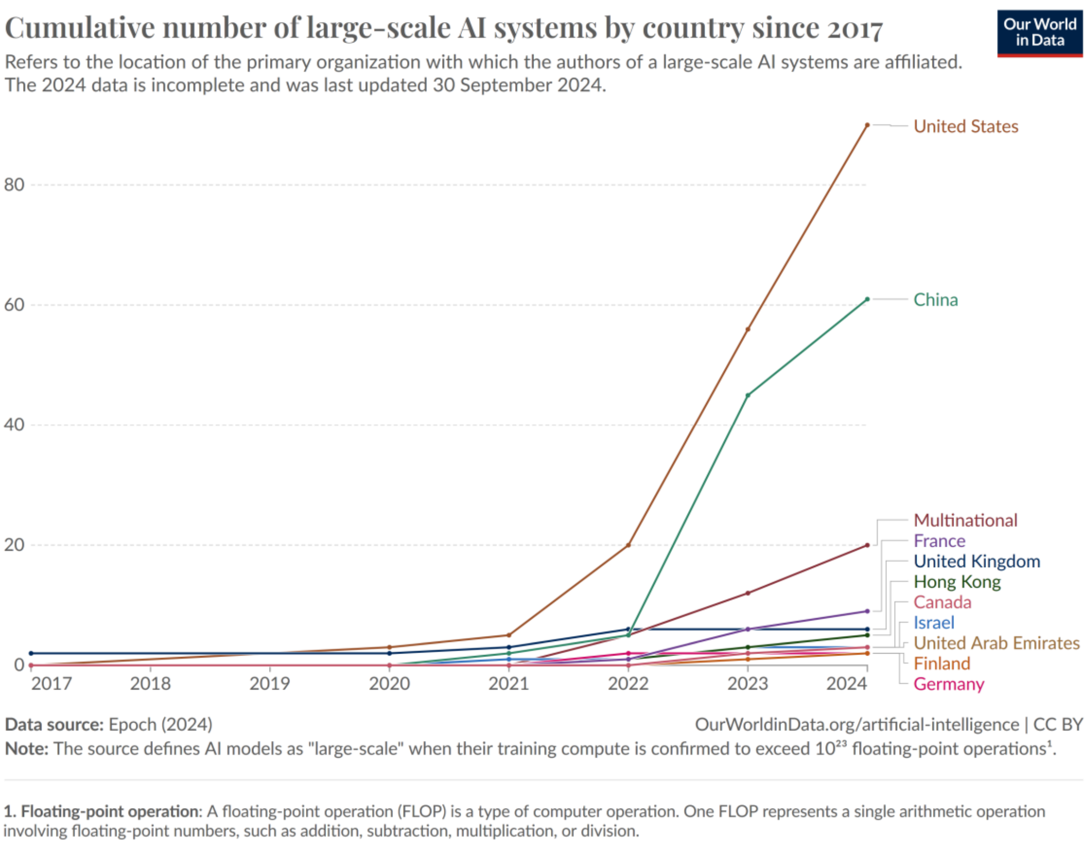
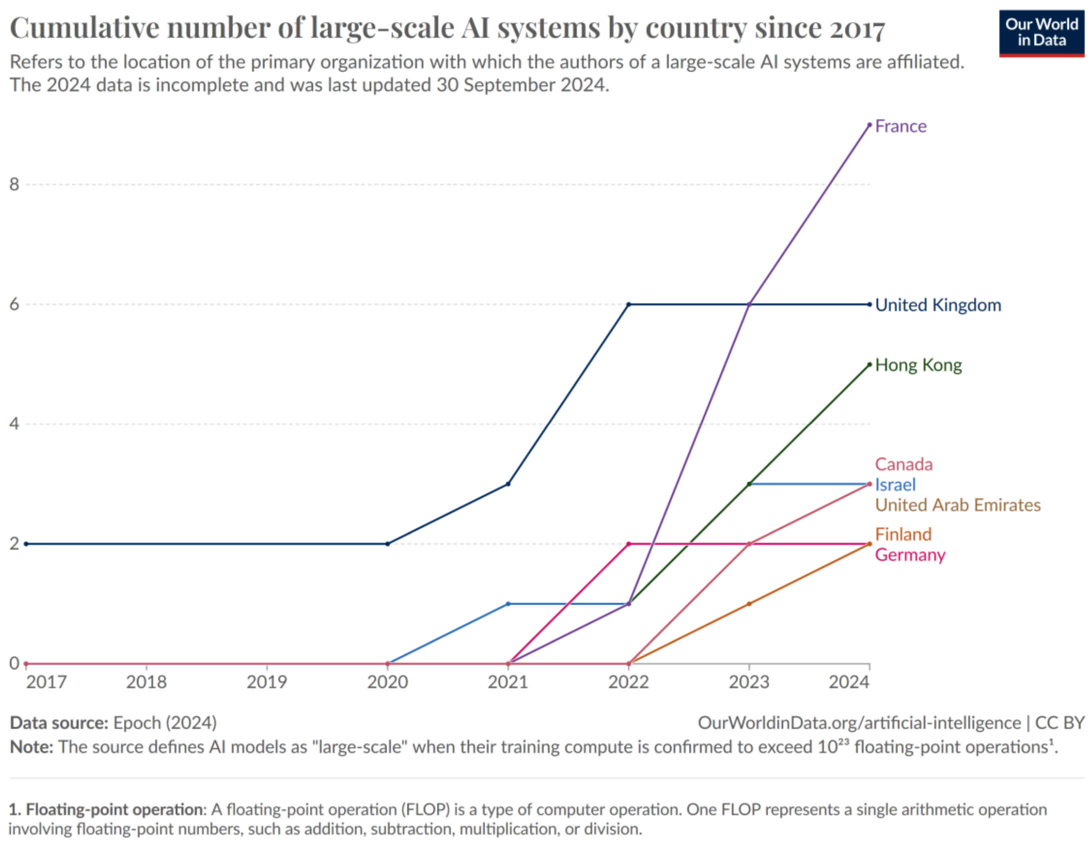


Figure 41: Major language models by country, here excluding USA, China and multi-national (2024)



Source for both charts: https://ourworldindata.org/grapher/cumulative-number-of-large-scale-ai-systems-by-country based on data from Epoch AI, retrieved on October 7, 2024

Looking at performance excluding the USA, China and the multinational models, the result is a ranking in which France ranks ahead of the UK and Hong Kong (Figure 41). Germany is in last place, tied with Finland. However, this ranking may distort the performance of countries in the AI field, because while large language models are a very important basis for progress in generative AI, future AI innovations may also come from other areas. In addition, the application of AI in the industrial environment and in other sectors and fields of application plays an important role (as discussed in more detail in sections 3 and 4). It would be interesting to evaluate all relevant ("notable") ML models here, not just large language models. However, such an evaluation is not yet available.

6 Summary of the country comparisons and outlook

After analyzing the selected studies, the question of which countries are currently leading in AI research can be answered as follows:

- → Current AI research is mainly concerned with large language models, which require large amounts of computing capacity and data for training. The United States of America is the clear leader in research and innovation in this area of AI. This can be seen, for example, in the number of large-scale AI systems developed, such as ChatGPT from Open AI or Gemini from Alphabet and Google.
- → China lags behind the USA in the area of large language models. Depending on the source, China needs one to three years to catch up. In order to reach the current level of US models, the embargo on American high-performance GPUs today do not seem as important as was expected in the past as Chinese researchers are increasinly utilizing distributed computing concepts.
- → Like China, European countries have largely overslept the development of large language models. In the statistics of large AI models from Europe, France is in the lead, followed by the UK, Israel and Germany, on a par with Finland. However, a catch-up development like in China cannot be observed yet in Europe, depite some major government support measures. In Europe, there is also a debate as to whether Europe should participate in the race for large-scale language models at all, or whether it should instead focus on its own research and implementation strategies.

The analysis also revealed approaches to the question of how quality levels can be differentiated in AI research. These can be summarized as follows:

- → Large language models are very demanding in terms of the hardware required and the integration of large amounts of data. And they require corresponding expertise in model development. Large language models therefore currently represent the highest level of quality in AI research.
- → AI research is extremely dynamic and is characterized by leaps in innovation. The development of the first large language models based on new machine learning models was one such innovative leap. Further leaps can be expected in the future, which will also offer other classifications of quality levels. Currently, a combination of modern ML models with older AI research directions, known as hybrid AI, is expected to drive development forward. If the expectations for hybrid AI are confirmed, older AI research directions would become more relevant again and require a corresponding reassessment of the quality level classification. In addition, smaller models that are trained for specific contexts and only reference the large language models in the background could lead to decreasing hardware requirements for new systems. AI systems could become more powerful and at the same time require less hardware, data and training in the future.

Overall, it has been shown that a detailed analysis of both performance indicators and quality definitions is necessary in order to adequately describe and evaluate the research and innovation field of artificial intelligence. Simple indicators often narrow the view and ignore the options that arise from new combinations of research fields and application contexts.

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