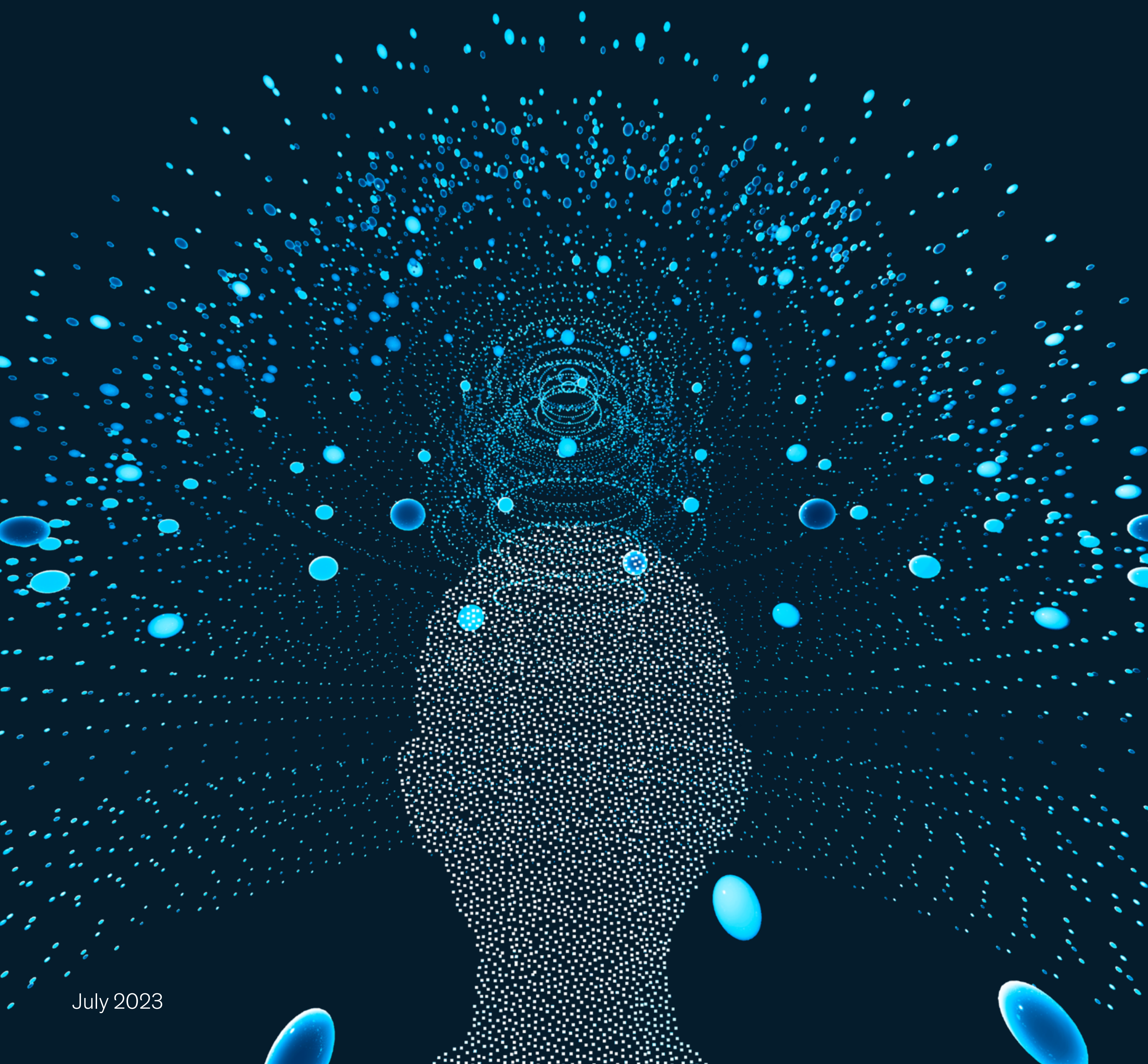
McKinsey Digital

Technology Trends Outlook 2023



July 2023

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McKinsey & Company is a global management consulting firm, deeply committed to helping institutions in the private, public, and social sectors achieve lasting success. For more than 90 years, our primary objective has been to serve as our clients' most trusted external adviser. With consultants in more than 100 cities in over 60 markets, across industries and functions, we bring unparalleled expertise to clients all over the world. We work closely with teams at all levels of an organization to shape winning strategies, mobilize for change, build capabilities, and drive successful execution.

Contents

Introduction

After a tumultuous 2022 for technology investment and talent, the first half of 2023 has seen a resurgence of enthusiasm about technology's potential to catalyze progress in business and society. Generative AI deserves much of the credit for ushering in this revival, but it stands as just one of many advances on the horizon that could drive sustainable, inclusive growth and solve complex global challenges.

To help executives track the latest developments, the McKinsey Technology Council has once again identified and interpreted the most significant technology trends unfolding today. While many trends are in the early stages of adoption and scale, executives can use this research to plan ahead by developing an understanding of potential use cases and pinpointing the critical skills needed as they hire or upskill talent to bring these opportunities to fruition.

Our analysis examines quantitative measures of interest, innovation, and investment to gauge the momentum of each trend. Recognizing the long-term nature and interdependence of these trends, we also delve into underlying technologies, uncertainties, and questions surrounding each trend. This year, we added an important new dimension for analysis—talent. We provide data on talent supply-and-demand dynamics for the roles of most relevance to each trend. (For more, please see the sidebar, "Research methodology," on page 9.)

New and notable

All of last year's 14 trends remain on our list, though some experienced accelerating momentum and investment, while others saw a downshift. One new trend, generative AI, made a loud entrance and has already shown potential for transformative business impact.

This new entrant represents the next frontier of AI. Building upon existing technologies such as applied AI and industrializing machine learning, generative AI has high potential and applicability across most industries. Interest in the topic (as gauged by news and internet searches) increased threefold from 2021 to 2022. As we recently wrote, generative AI and other foundational models change the AI game by taking assistive technology to a new level, reducing application development time, and bringing powerful capabilities to nontechnical users. Generative AI is poised to add as much as $4.4 trillion in economic value from a combination of specific use cases and more diffuse uses—such as assisting with email drafts—that increase productivity. Still, while generative AI can unlock significant value, firms should not underestimate the economic significance and the growth potential that underlying AI technologies and industrializing machine learning can bring to various industries.

About the McKinsey Technology Council

Technology is changing everything in our work and home lives. The McKinsey Technology Council helps understand what is coming and how it will affect us all—taking a look around the corner toward the futures that technology change can unlock as well as the tough questions it raises.

We look at a spectrum of technologies, from artificial intelligence to computing to biology, and their applications across all sectors, from mining to entertainment. We also look at the science, how it translates into engineering, and when it will accelerate to impact—at scale and around the world. The McKinsey Technology Council brings together a global group of more than 100 scientists, entrepreneurs, researchers, and business leaders. We research, debate, inform, and advise, helping executives from all sectors navigate the fast-changing technology landscape. Together, we are shaping the future.

—**Lareina Yee,** senior partner, McKinsey; chair, McKinsey Technology Council

+15%

tech trends job postings from 2021 to 2022

–13%

global job postings from 2021 to 2022

Investment in most tech trends tightened year over year, but the potential for future growth remains high, as further indicated by the recent rebound in tech valuations. Indeed, absolute investments remained strong in 2022, at more than $1 trillion combined, indicating great faith in the value potential of these trends. Trust architectures and digital identity grew the most out of last year's 14 trends, increasing by nearly 50 percent as security, privacy, and resilience become increasingly critical across industries. Investment in other trends—such as applied AI, advanced connectivity, and cloud and edge computing—declined, but that is likely due, at least in part, to their maturity. More mature technologies can be more sensitive to short-term budget dynamics than more nascent technologies with longer investment time horizons, such as climate and mobility technologies. Also, as some technologies become more profitable, they can often scale further with lower marginal investment. Given that these technologies have applications in most industries, we have little doubt that mainstream adoption will continue to grow.

Organizations shouldn't focus too heavily on the trends that are garnering the most attention. By focusing on only the most hyped trends, they may miss out on the significant value potential of other technologies and hinder the chance for purposeful capability building. Instead, companies seeking longer-term growth should focus on a portfolio-oriented investment across the tech trends most important to their business. Technologies such as cloud and edge computing and the future of bioengineering have shown steady increases in innovation and continue to have expanded use cases across industries. In fact, more than 400 edge use cases across various industries have been identified, and edge computing is projected to win double-digit growth globally over the next five years. Additionally, nascent technologies, such as quantum, continue to evolve and show significant potential for value creation. Our updated analysis for 2023 shows that the four industries likely to see the earliest economic impact from quantum computing—automotive, chemicals, financial services, and life sciences—stand to potentially gain up to $1.3 trillion in value by 2035. By carefully assessing the evolving landscape and considering a balanced approach, businesses can capitalize on both established and emerging technologies to propel innovation and achieve sustainable growth.

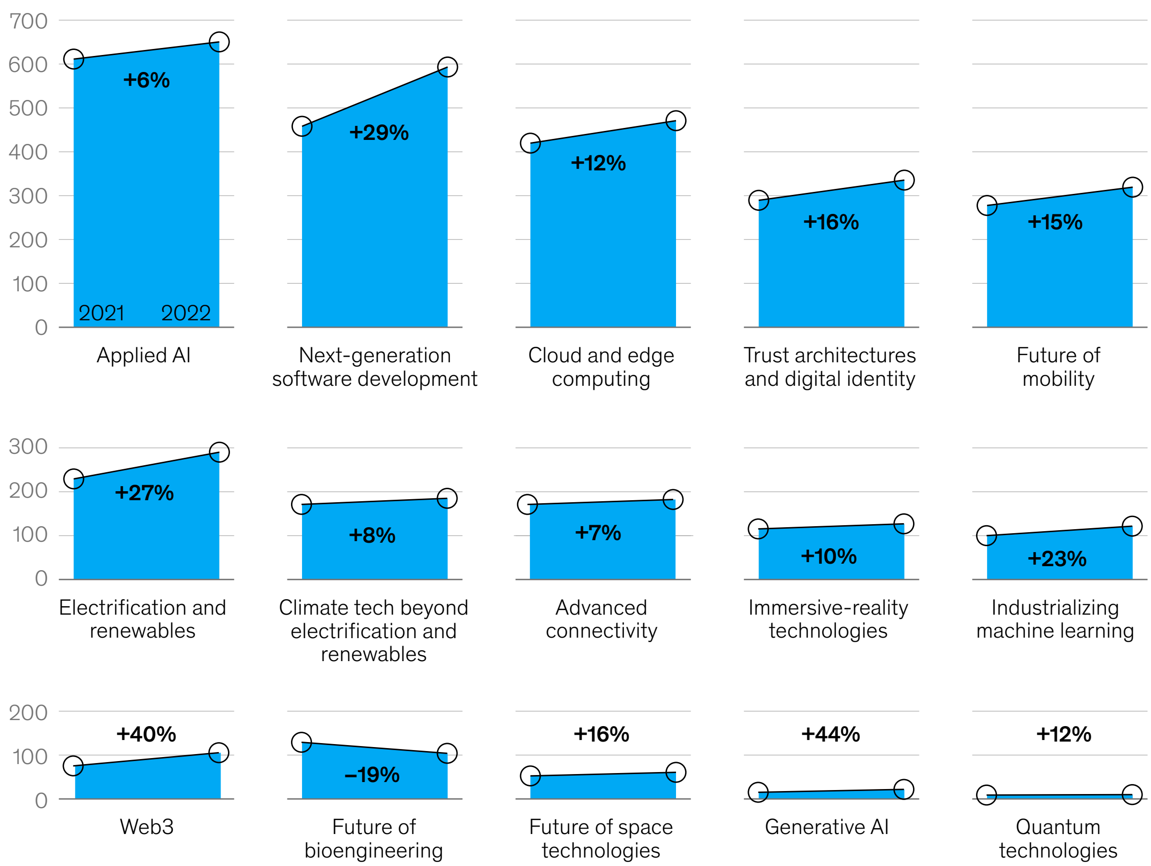
Tech talent dynamics

We can't overstate the importance of talent as a key source in developing a competitive edge. A lack of talent is a top issue constraining growth. There's a wide gap between the demand for people with the skills needed to capture value from the tech trends and available talent: our survey of 3.5 million job postings in these tech trends found that many of the skills in greatest demand have less than half as many qualified practitioners per posting as the global average. Companies should be on top of the talent market, ready to respond to notable shifts and to deliver a strong value proposition to the technologists they hope to hire and retain. For instance, recent layoffs in the tech sector may present a silver lining for other industries that have struggled to win the attention of attractive candidates and retain senior tech talent. In addition, some of these technologies will accelerate the pace of workforce transformation. In the coming decade, 20 to 30 percent of the time that workers spend on the job could be transformed by automation technologies, leading to significant shifts in the skills required to be successful. And companies should continue to look at how they can adjust roles or upskill individuals to meet their tailored job requirements. Job postings in fields related to tech trends grew at a very healthy 15 percent between 2021 and 2022, even though global job postings overall decreased by 13 percent. Applied AI and next-generation software development together posted nearly one million jobs between 2018 and 2022. Next-generation software development saw the most significant growth in number of jobs (Exhibit 1).

Exhibit 1

Job postings for fields related to tech trends grew by 400,000 between 2021 and 2022, with generative AI growing the fastest.

Tech trend job postings,[1] 2021–22, thousands



[1]Out of 150 million surveyed job postings. Job postings are not directly equivalent to numbers of new or existing jobs.
Source: McKinsey's proprietary Organizational Data Platform, which draws on licensed, de-identified public professional profile data

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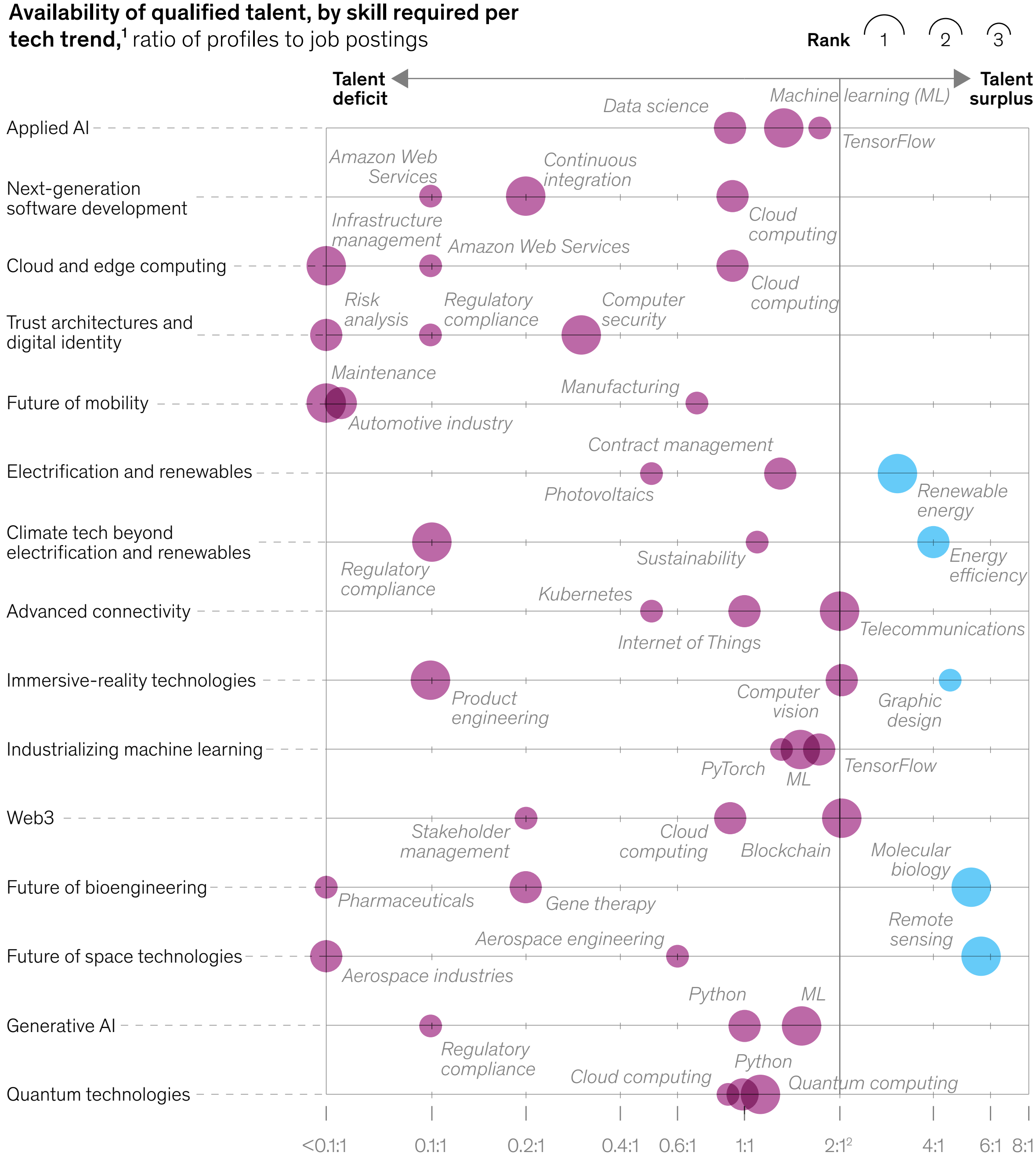
This bright outlook for practitioners in most fields highlights the challenge facing employers who are struggling to find enough talent to keep up with their demands. The shortage of qualified talent has been a persistent limiting factor in the growth of many high-tech fields, including AI, quantum technologies, space technologies, and electrification and renewables.

The talent crunch is particularly pronounced for trends such as cloud computing and industrializing machine learning, which are required across most industries. It's also a major challenge in areas that employ highly specialized professionals, such as the future of mobility and quantum computing (Exhibit 2).

Exhibit 2

Most fields related to these tech trends require skills where talent supply is low, while only a few fields have a talent surplus.

Availability of qualified talent, by skill required per tech trend,[1] ratio of profiles to job postings



[1]The ratio of online profiles claiming each trend's most needed tech skills to all job postings requiring skill (logarithmic scale).
[2]Benchmark: 2 profiles with skill per job posting. Average talent supply–demand ratio benchmark based on skills listed for the 20 most common jobs.
Source: McKinsey's proprietary Organizational Data Platform, which draws on licensed, de-identified public professional profile data

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The 15 tech trends

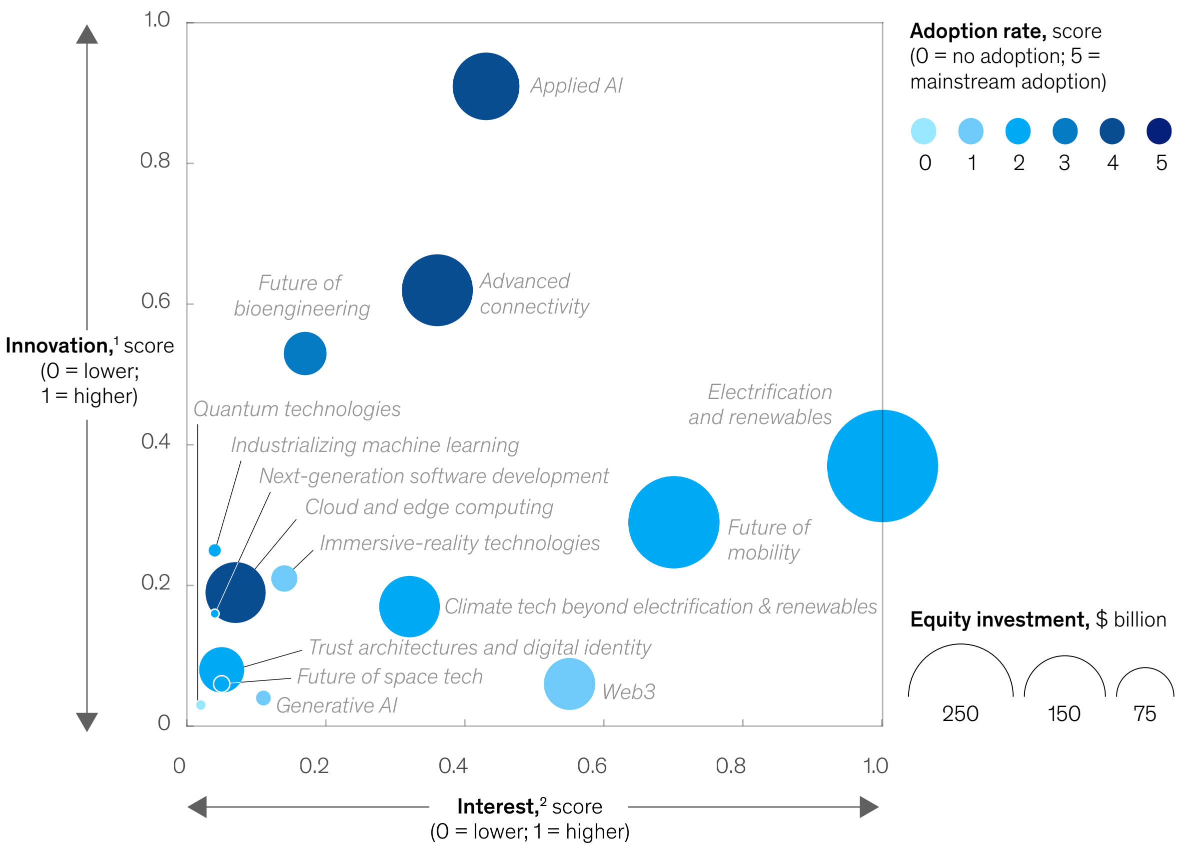
This report lays out considerations for all 15 technology trends. We grouped them into five broader categories to make it easier to consider related trends: the AI revolution, building the digital future, cutting-edge engineering, compute and connectivity frontiers, and a sustainable world. Of course, when considering trend combinations, there's significant power and potential in looking across these groupings.

To describe the state of each trend, we developed scores for innovation (based on patents and research) and interest (based on news and web searches). We also counted investments in relevant technologies and rated their level of adoption by organizations (Exhibit 3).

Exhibit 3

We described each trend by scoring innovation and interest, and we also counted investments and rated their level of adoption by organizations.

Innovation, interest, investment, and adoption, by technology trend, 2022



Note: Innovation and interest scores for the 15 trends are relative to one another. All trends exhibit high levels of innovation and interest compared with other topics and are also attracting significant investment.
[1]The innovation score combines the 0–1 scores for patents and research, which are relative to the trends studied. The patents score is based on a measure of patent filings, and the research score is based on a measure of research publications.
[2]The interest score combines the 0–1 scores for news and searches, which are relative to the trends studied. The news score is based on a measure of news publications, and the searches score is based on a measure of search engine queries.

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Research methodology

To assess the development of each technology trend, our team collected data on five tangible measures of activity: search engine queries, news publications, patents, research publications, and investment. For each measure, we used a defined set of data sources to find occurrences of keywords associated with each of the 15 trends, screened those occurrences for valid mentions of activity, and indexed the resulting numbers of mentions on a 0–1 scoring scale that is relative to the trends studied. The innovation score combines the patents and research scores; the interest score combines the news and search scores. (While we recognize that an interest score can be inflated by deliberate efforts to stimulate news and search activity, we believe that each score fairly reflects the extent of discussion and debate about a given trend.) Investment measures the flows of funding from the capital markets into companies linked with the trend. Data sources for the scores include the following:

— *Patents.* Data on patent filings are sourced from Google Patents.

— *Research.* Data on research publications are sourced from the Lens (www.lens.org).

— *News.* Data on news publications are sourced from Factiva.

— *Searches.* Data on search engine queries are sourced from Google Trends.

— *Investment.* Data on private-market and public-market capital raises are sourced from PitchBook.

— *Talent demand.* Number of job postings is sourced from McKinsey's proprietary Organizational Data Platform, which stores licensed, de-identified data on professional profiles and job postings. Data is drawn primarily from English-speaking countries.

In addition, we updated the selection and definition of trends from last year's study to reflect the evolution of technology trends:

— The generative-AI trend was added since last year's study.

— We adjusted the definitions of electrification and renewables (previously called future of clean energy) and climate technologies beyond electrification and renewables (previously called future of sustainable consumption).

— Data sources were updated. This year, we included only closed deals in PitchBook data, which revised downward the investment numbers for 2018–22. For future of space technologies investments, we used research from McKinsey's Aerospace & Defense Practice.

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The AI revolution

Applied AI

The trend—and why it matters

With AI capabilities, such as machine learning (ML), computer vision, and natural-language processing (NLP), companies in all industries can use data and derive insights to automate processes, add or augment capabilities, and make better decisions. McKinsey research estimates the potential economic value at stake from applied AI to be $17 trillion to $26 trillion, and the share of companies pursuing that value has been increasing. The annual McKinsey Global Survey on the state of AI shows that the proportion of responding organizations adopting AI more than doubled from 20 percent in 2017 to 50 percent in 2022. The 2022 survey also indicated that adopting AI can have significant financial benefits: 25 percent of respondents attributed 5 percent or more of their companies' EBIT to AI. However, organizational, technical, ethical, and regulatory issues should be resolved before businesses can realize the technology's full potential.

Applied AI

Scoring the trend

High innovation and investment scores for applied AI are commensurate with its large potential impact. Each year from 2018 to 2022, applied AI has had the highest innovation scores of all the trends we studied, and its investment score also ranks in the top five. Perhaps unsurprisingly, in 2022, demand for talent in applied AI was also highest among all trends.

Adoption rate score, 2022

Equity investment, 2022, $ billion

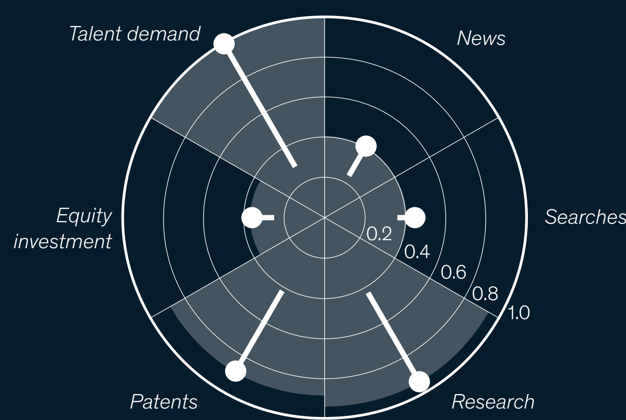
104

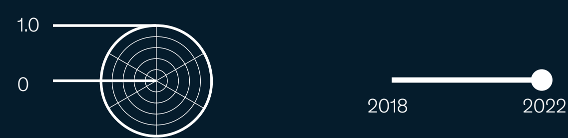
Job postings, 2021–22, % difference

+6

Industries affected: *Aerospace and defense; Agriculture; Automotive and assembly; Aviation, travel, and logistics; Chemicals; Construction and building materials; Consumer packaged goods; Education; Electric power, natural gas, and utilities; Financial services; Healthcare systems and services; Information technology and electronics; Media and entertainment; Metals and mining; Oil and gas; Pharmaceuticals and medical products; Public and social sectors; Real estate; Retail*

Score by vector (0 = lower; 1 = higher)





Talent demand Ratio of actual skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

These are some recent developments involving applied AI:

— *Investment fuels enhanced AI capabilities.* Although investments in AI were down to $104 billion in 2022 from a high of $146.8 billion in 2021, they continue to pace ahead of 2018–20 levels, which averaged $73.5 billion. With investments flowing, AI continues to post state-of-the-art results with continuous improvements in areas such as model accuracy. For example, the cost to train image classification systems has decreased by 63.6 percent, and training times have improved by 94.4 percent since 2018.[1] However, additional potential for applied AI could be unlocked by combining it with new emerging AI technology. For example, the foundation models underlying generative AI could process large amounts of unstructured manufacturing data, such as notes and logs, to enrich current AI solutions that optimize performance.

— *Policy makers accelerate regulatory actions to curb AI misuse.* As AI technology advances, so too has its potential for misuse: the AIAAIC Repository, which tracks incidents related to the ethical misuse of AI, algorithms, and automation, indicates that the number of controversies involving AI has increased by 26 times since 2012. Algorithmic fairness, bias, and misuse have become mainstream concerns. An analysis of legislative records in 127 countries shows that the number of laws passed containing the words "artificial intelligence" grew from one in 2016 to 37 in 2022. Prompted by the accelerated development of AI by private firms, the European Union's AI Act—which regulates foundational AI models—is nearing law status following parliamentary committee approval. Meanwhile, the McKinsey Global Survey on the state of AI indicates that there has been no substantial increase in organizations' reported mitigation of AI-related risks relative to the increase in AI use.

— *Global AI adoption plateaus—for now.* While AI adoption globally is more than double that in 2017, the proportion of organizations using AI has leveled off to around 50 percent to 60 percent in recent years. However, companies that have already adopted AI nearly doubled the number of capabilities they use, such as natural-language generation or computer vision, from 1.9 in 2018 to 3.8 in 2022.[2]

'We haven't found an industry or business function that couldn't enhance its performance through applying AI. But capturing the value of AI is a journey that requires taking action across multiple dimensions, from talent to technology.'

– Michael Chui, partner, Bay Area

[1] Daniel Zhang et al., *Artificial Intelligence Index Report 2022*, AI Index Steering Committee, Stanford Institute for Human-Centered AI, Stanford University, March 2022.

[2] "The state of AI in 2022—and a half decade in review," QuantumBlack, AI by McKinsey, December 6, 2022.

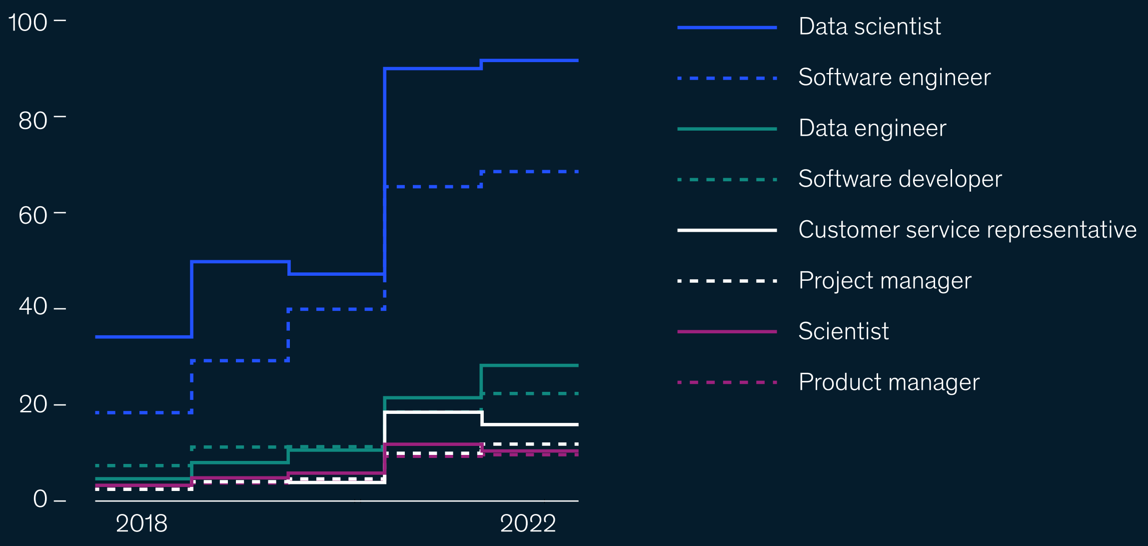
Talent market

Applied AI

Demand

Applied AI has seen rapid growth in demand for talent, with job postings more than tripling since 2018. Demand for data scientists and software engineers grew significantly in 2021 and saw moderate growth in 2022.

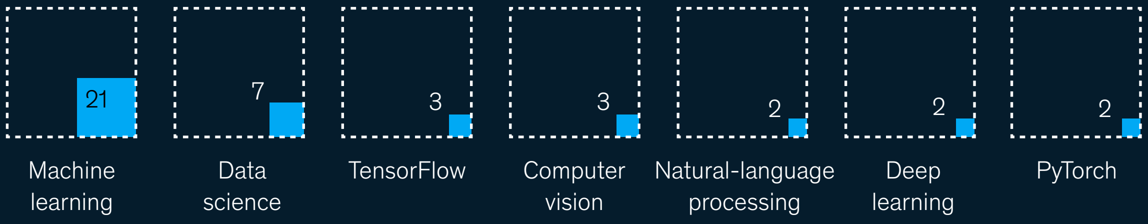
Job postings by title, 2018–22, thousands



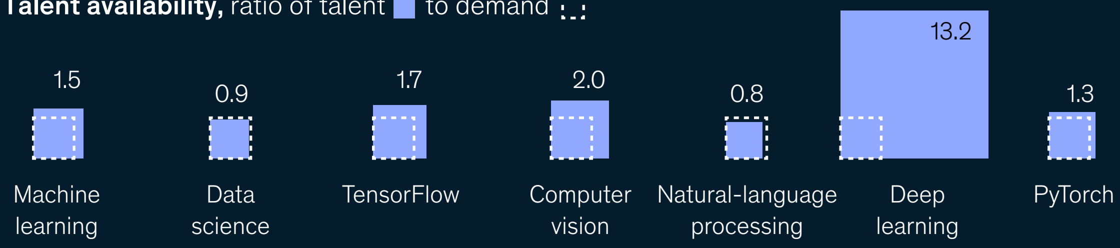
Skills availability

The demand for practitioners of machine learning, data science, NLP, and some associated tools is high compared with supply.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



'Applied AI has the potential to become more valuable and useful to companies in combination with generative AI. A key marker for the future will be how synergies between the two are captured to maximize value capture across organizations.'

– Carlo Giovine, partner, London

In real life

Real-world examples involving the use of applied AI include the following:

— Emirates Team New Zealand dramatically accelerated hydrofoil design and testing by using AI to train a "digital twin"—a digital replica of a sailor—to test designs in a simulated environment. By using the AI "sailor" to remove the bottleneck of human sailors performing the tests, the team reduced costs by 95 percent and was able to test ten times as many designs.

— Freeport-McMoRan deployed a custom-built AI model loaded with three years' worth of operating data to optimize production processes and total output at a copper mill. In doing so, it increased production by 10 percent while reducing capital expenditures on a planned expansion.

— Telkomsel built a new data analytics platform supplemented by AI-driven tools to better understand customers across thousands of microsegments. Using 9,000 data points per customer across more than 50 models, the company drives personalization by identifying the right way to interact with customers and offering the most relevant products and services.

Underlying technologies

AI comprises several technologies that perform cognitive-like tasks. These include the following:

— *Machine learning (ML).* This term refers to models that make predictions after being trained with data rather than following programmed rules.

— *Computer vision.* This type of ML works with visual data, such as images, videos, and 3-D signals.

— *Natural-language processing (NLP).* This type of ML analyzes and generates language-based data, such as text and speech.

— *Deep reinforcement learning.* This type of ML uses artificial neural networks and training through trial and error to make predictions.

Key uncertainties

The major uncertainties affecting applied AI include the following:

— *Lack of available resources*, such as talent and funding, might affect the pipeline of AI applications, despite technical advances in solutions for industrializing ML and in IT infrastructure.

— *Cybersecurity and privacy concerns*, notably on data risks and vulnerabilities, are prevalent—51 percent of survey respondents cited cybersecurity as a leading risk in 2022.

— *Regulation and compliance* might affect AI research and applications.

— *Ethical considerations*—including data governance, equity, fairness, and "explainability"—surround the responsible and trustworthy use of AI.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with applied AI:

— How might companies better determine which AI applications benefit them and their stakeholders most?

— What features make AI trustworthy and responsible and how should they be integrated into applications?

— What checks should companies put in place to guard against AI-related risks associated with data privacy and security, equity, fairness, and compliance?

— How will companies use generative AI in combination with applied AI to maximize potential synergies or differentiate when it makes sense to use one approach over the other?

Industrializing machine learning

The trend—and why it matters

Industrializing machine learning (ML), commonly referred to as ML operations, or MLOps, refers to the engineering practices needed to scale and sustain ML applications in an enterprise. These practices are enabled and supported by an ecosystem of technical tools that is rapidly improving, both in functionality and interoperability. MLOps tools can help companies transition from pilot projects to viable business products, accelerate the scale-up of analytics solutions, identify and resolve issues in production, and improve teams' productivity. Experience suggests that organizations that industrialize ML successfully can shorten the production time frame for ML applications (from proof of concept to product) by about eight to ten times and reduce development resources by up to 40 percent.[3] Industrialized ML was pioneered by a small number of leading companies, but adoption is now spreading as more companies use AI for a wider range of applications.

Industrializing machine learning

Scoring the trend

Scores across news, searches, publications, and patents increased significantly, while demand for talent has nearly quadrupled in the same time frame. These increases suggest that the use of methods for industrializing ML could widen in the years ahead

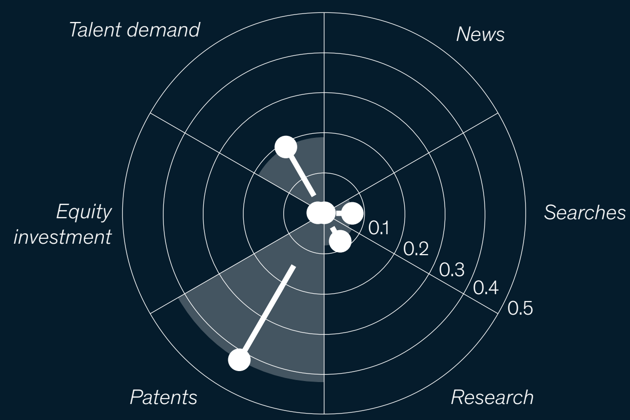
Adoption rate score, 2022

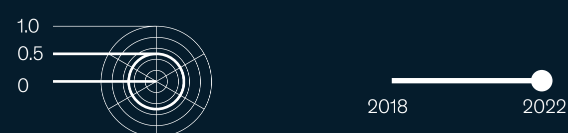
0 None · 1 · **2** · 3 · 4 · 5 Mainstream

Equity investment, 2022, $ billion	**Job postings, 2021–22,** % difference
3	+23

Industries affected: *Aerospace and defense; Automotive and assembly; Electric power, natural gas, and utilities; Financial services; Information technology and electronics; Media and entertainment; Metals and mining; Oil and gas; Pharmaceuticals and medical products; Telecommunications*

Score by vector (0 = lower; 1 = higher)





Talent demand Ratio of actual skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

[3] Based on observations from ML operations deployment in a series of large-scale analytics transformations supported by McKinsey.

Latest developments

These are some recent developments involving industrializing ML:

— *Companies increasingly commit to industrializing ML.* Investments into companies in the ML industrialization space reached a high of $4.7 billion in 2021 and remained strong throughout 2022 at a cumulative $3.4 billion. With investments flowing, ML decision makers have also doubled down on their commitments: 85 percent of respondents to a ClearML survey indicated that they had a dedicated MLOps budget in 2022. IDC predicts that 60 percent of enterprises will have implemented MLOps by 2024. Such investments could prove wise, as our own research finds that companies seeing higher returns from AI are more likely to engage in ML industrialization.

— *The ecosystem rapidly evolves through acquisitions and new offerings.* The year 2022 was marked by significant consolidation, partnerships, and new releases. Altair acquired RapidMiner, Snowflake acquired Myst AI, McKinsey acquired Iguazio, and Hewlett Packard Enterprise acquired Pachyderm. Databricks announced MLflow 2.0, the successor to its highly popular open-source MLOps framework. Additionally, Gantry released a new type of MLOps offering—a platform that will determine real-time ML-model-production performance and how to optimize it. With continued investment, the landscape is bound to change quickly.

‘We are at an inflection point with artificial intelligence. Generative AI has captured both mainstream and business imaginations. Organizations that are willing to continuously learn and adapt their processes, ways of working, and technology to industrialize ML will succeed in building the muscle needed to leverage AI at scale and unlock its value.’

– Nayur Khan, partner, London

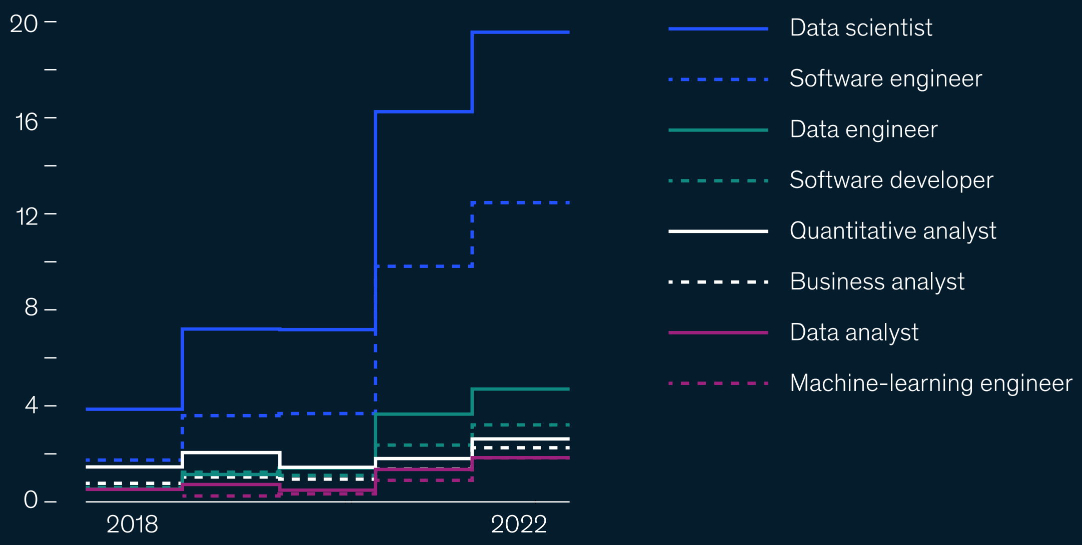
Talent market

Industrializing machine learning

Demand

Talent acquisition at scale is a key factor for scalable growth and implementation of ML and AI. As AI adoption has increased, job postings for related roles have increased, growing nearly fourfold since 2018 and 23.4 percent from 2021 to 2022. Key roles needed to develop and implement industrializing technology include data scientists, software engineers, data engineers, and ML engineers.[1]

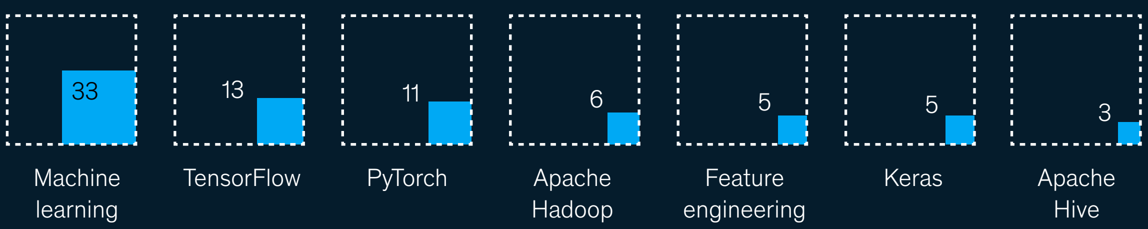
Job postings by title, 2018–22, thousands



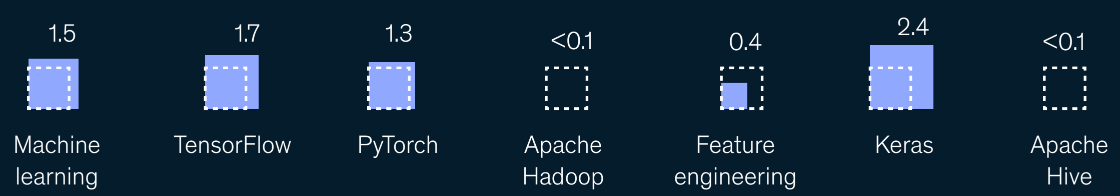
Skills availability

Companies expanding their ML initiatives need professionals with many technical skills that are often in short supply, such as Kafka and Hive. Moreover, those professionals now need more software engineering (SWE) skills than has historically been the case (for example, data scientists must have stronger SWE skills for MLOps than are needed to perform research experiments).

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



[1]See also the "Cloud and edge computing" trend for skills required for cloud-based industrialized-ML platforms.

In real life

Real-world examples involving industrializing ML include the following:

— To transform its entire organization with AI, a global pharmaceutical company deployed an enterprise-wide ML industrialization capability to increase productivity, speed, and reliability; reduce risk; and ensure regulatory compliance and trust at scale.

— A global metals producer rapidly scaled up analytics use cases across its business to unlock tens of millions of dollars of run rate impact each year. MLOps practices were essential to enabling the pace and sustainability of this transformation.

— A global oil and gas company integrated MLOps into the heart of the company's AI/ML capabilities, reducing the time to build and deploy ML solutions by over 50 percent and realizing more than $250 million in annualized impact from AI-driven operations optimizations.

— Vistra partnered with McKinsey to develop more than 400 AI models and used MLOps to standardize their deployment and maintenance. This enabled the company to optimize the thermal efficiency across 26 of its plants, generate more than $20 million in energy savings, and abate about 1.6 million tons of carbon per year.

Underlying technologies

Software solutions enable the various stages of the ML workflow, which are as follows:

— *Data management.* Automated data-management software improves data quality, availability, and control in feeding the ML system.

— *Model development.* Tooling is used to build and optimize ML models, engineer features, and standardize processes.

— *Model deployment.* Provision tooling tests and validates ML models, brings them into production, and standardizes processes.

— *Live-model operations.* Software maintains or improves the performance of models in production.

— *Additional hardware tools and technologies.* Other tools and technologies, such as cloud computing and domain-specific architectures, improve access to high-capacity compute for ML workflows.

'We see AI teams siloed, which leads to a lack of standardized industrialization processes and technologies across an organization. Solving for that is critical to truly unlocking AI at scale.'

– Bruce Philp, partner, Boston

Key uncertainties

Companies and leaders may want to consider a few questions when moving forward with industrializing ML:

- *Up-front investment and resources* will be required to establish industrialized ML in organizations.
- *Processes and accountability* will be crucial for maintaining ML solutions at industrial scale.
- *A fast-evolving market* will require organizations to avoid vendor lock-in so they can realize value from newer offerings provided by players outside their existing vendor ecosystem.
- *Potential for misaligned capabilities* will need to be avoided by ensuring that organizations are investing at the right level and in the right solutions for their specific use case needs.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with industrializing ML:

- With the proliferation of new technologies in ML, how should organizations select the ones along the ML workflow that are most relevant to their needs?
- How will industrialized ML change organizations, their operating models, and their engineering roles?
- How can organizations define roles of accountability to ensure the trustworthy and responsible use of AI/ML as industrialized ML proliferates?
- With the emergence and acceleration of generative AI, how will MLOps practices and the technology ecosystem evolve?

Generative AI

The trend—and why it matters

Generative AI marks a tipping point for AI. Unlike previous AI, it can enable the creation of new, unstructured content—such as text, audio, video, images, code, simulations, and even protein sequences or consumer journeys—based on information it learns from similar formats of unstructured data. And the technology at its core, foundational models, can be adapted to a wide range of tasks—for example, summarization, classification, and drafting. In contrast, previous generations of AI models were often "narrow," meaning they could perform just one task.

In a business context, generative AI could not only unlock novel use cases but also speed up, scale, or otherwise improve existing ones. Generative AI has the potential to redefine businesses and value chains by enabling the development of new products and revenue streams, enhancing customer experience. Its impact is expected to materialize most, however, in improving employee productivity and experience.

In these early days, we see companies in many industries using generative AI primarily as an assistive technology to create first drafts, generate hypotheses, or assist experts in performing a task faster or better. All of these uses have two things in common: there is an expert in the loop to check the output, especially for hallucinations (inaccurate content produced by the application) and intellectual-property (IP) issues, and they are used in an existing workflow, which eases adoption and change management. It might be some time before organizations advance generative-AI-based applications from assistive to fully automated for high-stakes use cases.

Generative AI

Scoring the trend

Although generative AI ranked comparatively low on interest, investment, and innovation in 2022, the threefold increase in number of searches reflects a strong sense of excitement about the trend, and we anticipate significant growth across metrics in 2023.

Adoption rate score, 2022

0 1 2 3 4 5

None Mainstream

Equity investment, 2022, $ billion

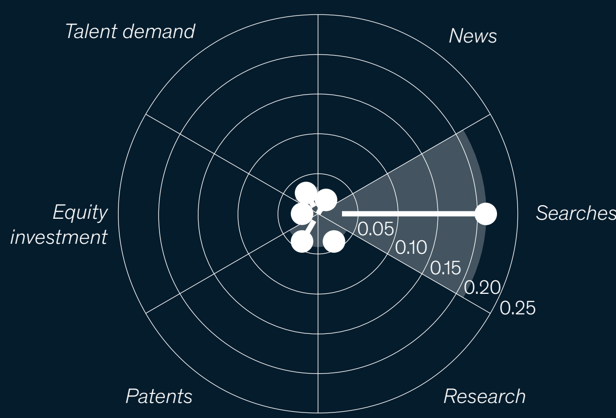
5

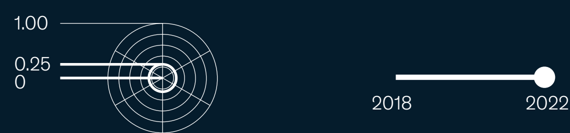
Job postings, 2021–22, % difference

+44

Industries affected: *Consumer packaged goods; Financial services; Healthcare systems and services; Information technology and electronics; Media and entertainment; Oil and gas; Pharmaceuticals and medical products; Retail; Telecommunications*

Score by vector (0 = lower; 1 = higher)





Talent demand Ratio of actual skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

These are some recent developments involving generative AI:

- *Global excitement about the trend paves the way for corporate pilots.* Generative AI has witnessed a flurry of investment activity. For example, venture capital investments increased 425 percent from 2020, and Microsoft invested $10 billion in a multiyear deal with OpenAI. With nearly 80 percent of current AI research focused on generative AI, it should come as no surprise that companies in industries ranging from financial services to life sciences have begun experimenting with enterprise use cases. We also see that a range of start-ups have successfully developed their own models—for example, Cohere, Anthropic, and AI21 Labs, among others, build and train their own large-language models (LLMs). Additionally, other players in the field, such as Cohere, have been able to provide a higher level of IP protection, consumer privacy, and lower cost for LLMs that larger companies may want to have in their environments. Many others are building on top of LLM platforms provided by others or are extending open-source models. Alongside these start-ups, tech giants like Google are also making significant strides. In May 2023, Google announced several new generative-AI-powered features, including the Search Generative Experience and a new LLM called PaLM 2, which will power its Bard chatbot, among other Google products. Further, we saw significant investments by software providers like Salesforce to integrate generative-AI capabilities into their existing products.
- *GPT-4 demonstrates a significant advancement over its predecessors.* The widely anticipated release of GPT-4 heralds increased functionality and performance over previously available models, such as improved scores across more than 30 academic and professional exams. Whereas GPT-3 performed in the bottom 10 percent of bar exam takers, GPT-4 performed in the top 10 percent. In addition, GPT-4 can now use both images and text as inputs, process up to 25,000 words (versus 4,000 with GPT-3), and is 40 percent more likely to generate accurate responses. Several complex applications have been enabled, such as the use of multimodal inputs (for example, text and images) and the orchestration of a sequence of actions to complete tasks such as devising new recipes (for example, through applications such as AutoGPT and BabyAGI).[4]
- *Large cloud and technology companies become active in the field of hardware accelerator designs.* Google developed its fourth-generation tensor processing unit (TPU v4), for example, which has enabled an approximate tenfold increase in system performance compared with previous versions.[5] Similarly, consumer hardware and edge systems are becoming available with specific designs to run LLMs more efficiently (for example, Apple's Neural Engine).[6]

'We often get asked by executives if generative AI is hype or a fundamental shift—the answer is both. From a scientific point of view, foundational models are not hype—they comprise a new class of AI that is elegant in its simplicity yet incredibly powerful in its ability to be tuned to perform many tasks in a humanlike manner. From a business point of view, these technologies have the potential to fundamentally disrupt entire categories.'

– Delphine Nain Zurkiya, senior partner, Boston

[4] Samantha Murphy Kelly, "5 jaw-dropping things GPT-4 can do that ChatGPT couldn't," CNN, March 16, 2023; Mark Sullivan, "Auto-GPT and BabyAGI: How 'autonomous agents' are bringing generative AI to the masses," *Fast Company*, April 13, 2023.
[5] Norm Jouppi and David Patterson, "Google's Cloud TPU v4 provides exaFLOPS-scale ML with industry-leading efficiency," Google, April 5, 2023.
[6] "Deploying transformers on the Apple Neural Engine," Apple, June 2022.

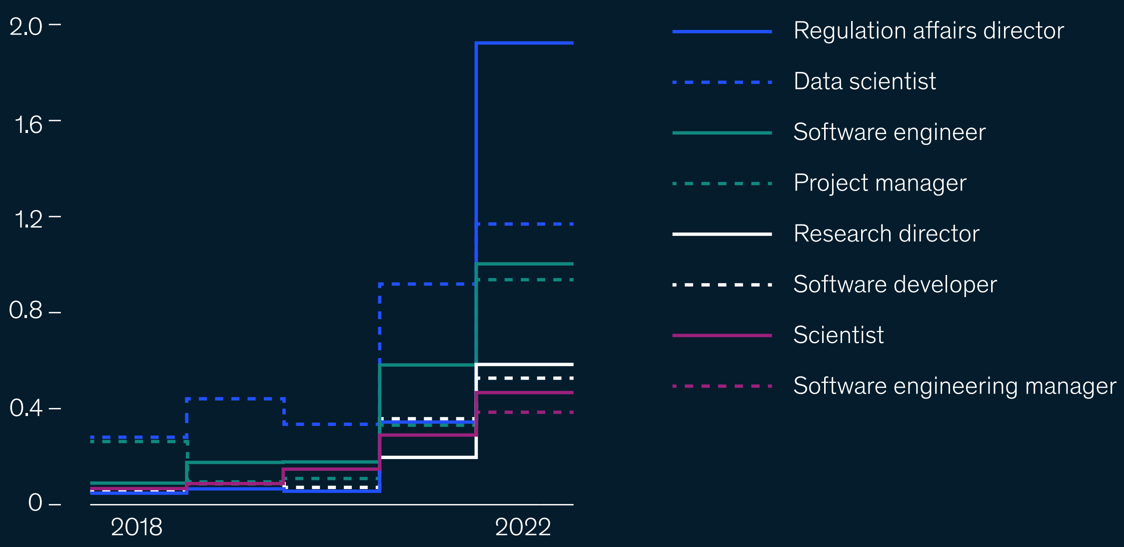
Talent market

Generative AI

Demand

Generative AI has seen strong and accelerating growth in talent demand since 2018. Hiring demand in 2023 will likely be significantly higher due to increased interest and investment. Job growth in this field took a different path from other tech trends, with postings for directors and managers outnumbering those for individual contributors. Our research indicates that many businesses are working fast to develop strategies for generative AI. A sharp increase in demand for regulation affairs directors indicates a desire to do so in a way that is cognizant of public concerns. The relatively low hiring rate for technical contributors may also indicate intentions to first validate value by piloting user-friendly, open-source models before investing heavily in building internal capabilities.

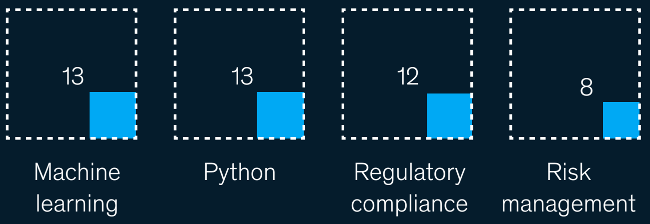
Job postings by title, 2018–22, thousands



Skills availability

There are significant skills overlaps with the "Applied AI" and "Industrializing machine learning" trends. Please refer to those trends for more detail.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand

In real life

Real-world examples involving the use of generative AI include the following:

- OTP Bank generated a Hungarian large-language model to enable more than 30 banking use cases across the organization, with an initial focus on spoken and text customer interactions, fraud detection, and cybersecurity.
- Exscientia is leveraging generative AI across all stages of its research and development process, claiming an average time from biological target to drug candidate of approximately 11 months compared with a 54-month industry average and at a cost that is 80 percent lower.
- Insilico Medicine developed a generative-AI model to predict clinical-trial success rates with a reported accuracy of 80 percent.
- Jasper, an AI-enabled content platform that leverages GPT-3 to generate marketing content (for example, copy writing, email, script writing) from provided user prompts, already boasts more than 100,000 customers.

Underlying technologies

Generative AI is powered by multiple types of software and hardware across the entire tech stack. These include the following:

- *Foundation models.* These are deep-learning models trained on vast quantities of unstructured, unlabeled data that can be used for a wide range of tasks out of the box or adapted to specific tasks through fine-tuning.
- *Application layer.* Typically, this is the interface that the end user interacts with (for example, chat).
- *Integration/tooling layer.* Sitting between the application layer and foundation model, this layer integrates with other systems to retrieve information, filter responses, save inputs and outputs, distribute work, and enable new features. Examples include the large-language-programming framework LangChain and vector databases such as Weaviate and Pinecone.
- *Hardware.* Specialized accelerator hardware, such as graphical processing units (GPUs) and tensor processing units (TPUs), enable model training and inference tasks on premises or via cloud hardware.

'The speed of advances in large-language-model capabilities have caught many executives off guard. It's important to keep in mind that the promise of transforming many manual, complex, and creative tasks comes with clear risks like erroneous outputs. In our experience, a successful approach often starts with identifying high-value, low-risk use cases, for example, coding assistance or hypothesis generation in R&D, and keeping a human in the loop.'

– Matej Macak, partner, London

Key uncertainties

The major uncertainties affecting generative AI include the following:

— *Cybersecurity and privacy concerns* are prevalent, notably around data leakage risks and vulnerabilities (including leakage of customer and protected data).

— *Ethical considerations* surround the responsible use of generative AI, including data governance, justice and fairness, accountability, and explainability.

— *Regulation and compliance* might affect research into generative AI and its potential applications.

— *Copyright ownership and protection* of content generated by open-source models remains an undefined issue.

— *Environmental impact* may increase as training models expend exponentially more computational resources.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with generative AI:

— Which workers will see their roles shift due to generative AI, and to what extent will they be affected?

— How will the cost of model creation evolve, and what impact will it have on competitive dynamics?

— Where can organizations establish competitive moats and ensure their defensibility?

— How should companies approach generative-AI-related risks, including data privacy and security, equity, fairness, compliance, and copyright protection?

— Will enterprise adoption experience the level of exponential growth seen in consumer adoption?

Building the digital future

Next-generation software development

The trend—and why it matters

Next-generation technologies are transforming the capabilities of engineers at every stage of the software development life cycle (SDLC)—from planning and testing to deployment and maintenance—and enabling more nontechnical employees to create applications. They can help simplify complicated tasks and reduce others to single commands. These technologies include AI pair programmers; low- and no-code platforms; infrastructure as code; automated integration, deployment, and testing; and emerging generative-AI tools. Adoption may be slow due to technical challenges, the need for large-scale retraining of developers and test engineers, and other organizational hurdles. However, the significant productivity gains seen in early trials suggest widespread usage is on the horizon.

Next-generation software development

Scoring the trend

News and patents have tripled since 2018, but investment and research publications have declined. Generative AI could shift scores.

Adoption rate score, 2022

0 1 **2** 3 4 5

None — Mainstream

Equity investment, 2022, $ billion

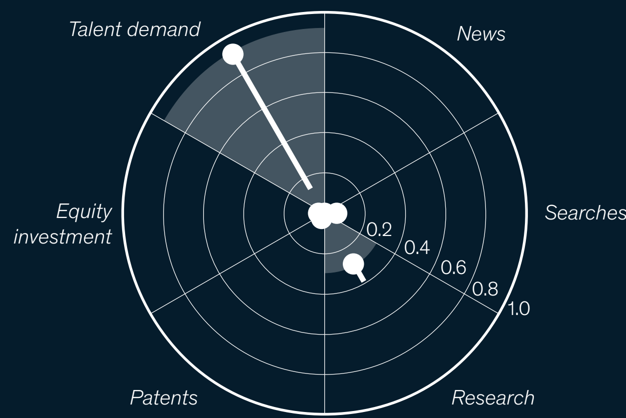
2

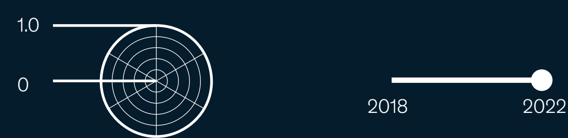
Job postings, 2021–22, % difference

+29

Industries affected: *Financial services; Information technology and electronics*

Score by vector (0 = lower; 1 = higher)





Talent demand Ratio of actual skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

These are some recent developments involving next-generation software development:

— *Generative-AI tools come to market.* The release of ChatGPT in late 2022 increased interest in using generative AI in software development. Several advanced tools are now available. In June 2022, GitHub released its AI pair-programming tool, GitHub Copilot, and Amazon has since released CodeWhisperer. These and other tools can write code more holistically and accurately than existing AI-based developer tools and generate code from natural-language prompts.

— *Research confirms that next-generation tools enhance developer productivity; nondevelopers could benefit soon as well.* Next-generation software can empower nontraditional engineers to participate in the development process and increase the productivity of existing software engineers. By 2026, Gartner predicts that 80 percent of low- and no-code tool users will sit outside of traditional IT organizations. AI-enabled tools can also enhance the productivity of traditional developers by automating routine tasks and suggesting solutions to problems. Our research shows that developers report time savings of 35 to 45 percent in code generation and 20 to 30 percent in code refactoring. They also report an improvement in happiness, flow, and fulfillment while using AI-enabled tools, which suggests that adopting these tools could help companies retain talent in a competitive talent market.

‘Developers are perhaps one of the most valuable assets for the modern digital enterprise, yet they spend well over 40 percent of their time on repetitive, low-value tasks that could be easily automated with a modern tool set.’

– Santiago Comella-Dorda, partner, Boston

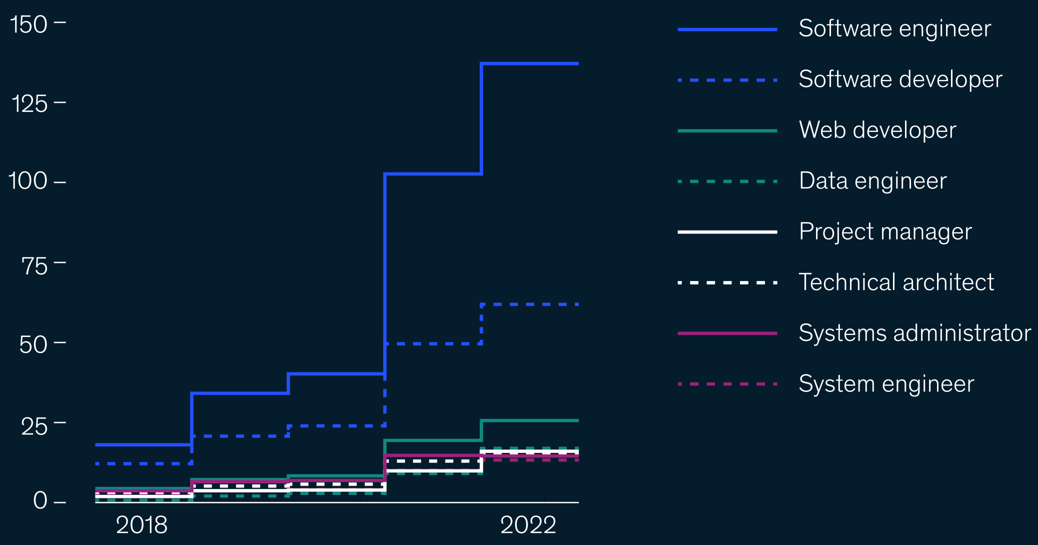
Talent market

Next-generation software development

Demand

Next-generation software development has seen the most dramatic growth in hiring demand among the tech trends, with job postings increasing sixfold since 2018. While macroeconomic adjustments and corrections to overhiring during the COVID-19 pandemic continue, we expect demand to keep rising as more companies adopt these tools. Postings for software engineers, developers, and data engineers have significantly increased since 2020, with the highest growth since 2021 in software engineer and data engineer roles.

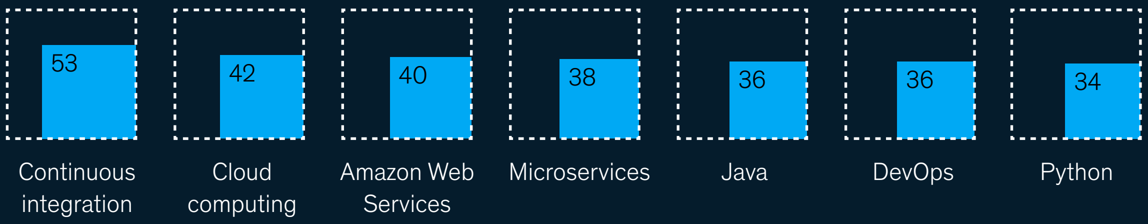
Job postings by title, 2018–22, thousands



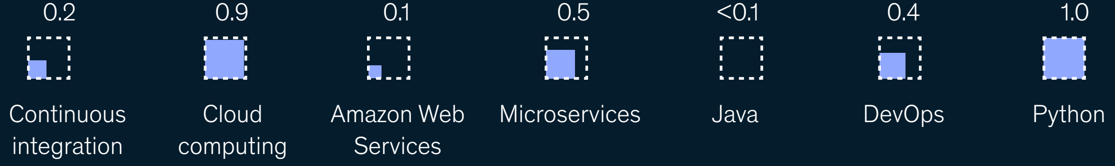
Skills availability

Although low- and no-code tools are likely to expand access to software roles, developing the tools takes highly technical skills, such as continuous integration and delivery (CI/CD), that are in in short supply.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



In real life

Real-world examples involving the use of next-generation software development include the following:

— Netflix built Netflix Test Studio (NTS), which supports a seamless streaming experience on many types of devices. NTS is a cloud-based automation framework for internal and external developers to deploy and execute tests. It abstracts away device differences and has a standard set of tools for assessing performance. NTS runs more than 40,000 long-running tests every day and allows remote tests of Netflix-ready devices.

— Citibank is investing in several tools for next-generation software development. For example, the company is a customer of and investor in Genesis, a low-code software development company. The Genesis platform tackles direct-automation use cases, including end-user computing (EUC) and client-servicing portals. Citibank has also partnered with Temenos, a core banking systems provider, for more than a decade. Temenos's software improved time-consuming and repetitive accounting and reporting tasks.

— Ticketmaster's mobile-development team began using GitLab's CI tools when small software changes were taking prohibitively long to execute. With GitLab's CI tools, the team reduced build time from two hours to eight minutes.

'We will see second-order effects play out over the next couple of years, such as emerging ways to apprentice new developers and evolutions in development team composition and career trajectories.'

– Martin Harrysson, senior partner, Bay Area

Underlying technologies

The technologies that power next-generation software development include the following:

— *Low- and no-code platforms.* Software development systems with graphics processing units, such as Microsoft Power Apps and Amazon Honeycode, make it easier for nondevelopers to build applications.

— *Infrastructure as code.* This is the process of configuring infrastructure, such as a data center, with machine-readable code, which enables rapid reconfiguration and version control. The cloud, for example, is infrastructure that is fully abstracted as code.

— *AI-generated code.* AI applications enable a user to input natural-language prompts or context from existing code to produce code recommendations.

— *Microservices and APIs.* These are self-contained, independently deployable pieces of code that can be coupled to form larger applications.

— *AI-based testing.* Next-generation software can use AI to automate unit and performance testing to reduce the amount of time developers spend on this task.

— *Automated code review.* These applications use AI or predefined rules that enable users to check source code.

Key uncertainties

The major uncertainties affecting next-generation software development include the following:

- *Relying on automated testing and reviews without having humans check the work* can lead to increased errors in software.
- *Growth in use of low- and no-code tools by nondevelopers could be limited* because of the need for experienced developers to monitor and debug applications.
- *Comprehensive monitoring and version control could become more difficult* due to uncoordinated changes and upgrades from multiple vendors.
- *Quality and security remain concerns with code generated by AI pair programmers,* particularly if they are not regularly updated with the latest standards or not trained on clean, fast code.
- *Customizing APIs is difficult* without significant time and effort.
- *APIs introduce security risks* by adding another attack layer that can be exploited.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with next-generation software development:

- To what extent can no-code tech reduce the need for traditional software developers?
- From a cultural standpoint, will teams—both developers and nondevelopers—embrace or resist changes in ways of working?
- What intellectual-property issues might affect AI-generated code?
- To what extent will business units take responsibility for the health of applications?
- How do organizations upskill engineers to know what good outputs from AI-enabled tools look like?

Trust architectures and digital identity

The trend—and why it matters

Digital-trust technologies enable organizations to manage technology and data risks, accelerate innovation, and protect assets. What's more, building trust in data and technology governance can enhance organizational performance and improve customer relationships. The underlying technologies include zero-trust architectures (ZTAs), digital-identity systems, and privacy engineering. Other technologies help build trust by building explainability, transparency, security, and bias minimization principles into the design of AI. The adoption of digital-trust technologies, however, has been hindered by a range of factors, including integration challenges, organizational silos, a lack of talent, and its limited consideration as a critical component of value propositions. Building a comprehensive trust-first risk mindset and capabilities requires top-down leadership and deliberate changes to multiple spheres of activity, from strategy and technology to user adoption.

Trust architectures and digital identity

Scoring the trend

While investment in trust architecture and digital-identity ventures grew about five times from 2018 to 2022 and talent demand grew significantly, other momentum scores are mixed.

Adoption rate score, 2022

0 1 **2** 3 4 5

None Mainstream

Equity investment, 2022,
$ billion

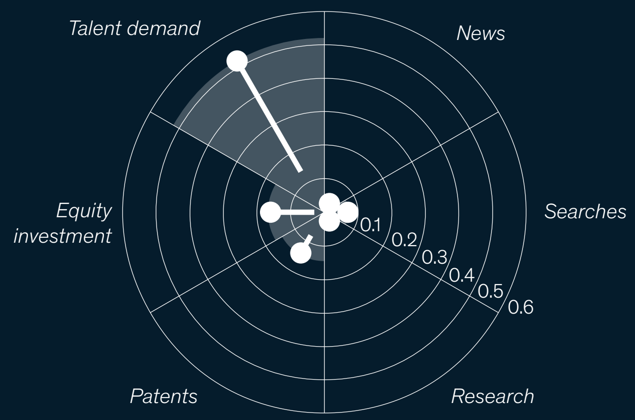
47

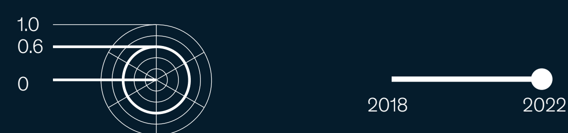
Job postings, 2021–22,
% difference

+16

Industries affected: *Aerospace and defense; Consumer packaged goods; Education; Financial services; Healthcare systems and services; Information technology and electronics; Media and entertainment; Pharmaceutical and medical products; Public and social sectors; Retail; Telecommunications*

Score by vector (0 = lower; 1 = higher)





Talent demand Ratio of actual skilled people to job vacancies

Equity investment Private- and public-market capital raises for relevant technologies

Patents Patent filings for technologies related to trend

News Press reports featuring trend-related phrases

Searches Search engine queries for terms related to trend

Research Scientific publications on topics associated with trend

Latest developments

These are some recent developments involving trust architectures and digital identity:

— *Technology resilience becomes increasingly vital to organizations.* In 2022, a McKinsey survey on technology resilience assessed the cybersecurity maturity level of more than 50 leading organizations across North America, Europe, and other developed markets. Ten percent of respondents indicated that they have been forced to rebuild from bare metal (for example, due to a catastrophic event), with 2 percent stating that they have already attempted to recover from bare metal but were unsuccessful.

— *Regulatory developments move industry toward privacy engineering.* Privacy controls to date have been focused primarily on data governance and semimanual solutions; however, new regulations on data localization and sharing, along with increasing AI and cloud usage, could push privacy engineering to become more important. In Europe, regulations such as 2022's NIS2 Directive, which mandates increased cybersecurity risk assessments, and the 2023 Data Governance Act, aimed at stimulating data sharing, make privacy engineering of the utmost importance. State data privacy laws in the United States (for example, in California, Colorado, Connecticut, Iowa, Utah, and Virginia) and federal sector-specific data laws (for example, the Health Insurance Portability and Accountability Act, or HIPPA, and the Children's Online Privacy Protection Act, or COPPA) call for a range of privacy compliance measures that require automated controls.

— *Explainability makes inroads, but generative AI could impede progress.* As regulators nudge organizations toward more transparency and customers' trust in digital increases, companies are increasingly adding an explainable AI (XAI) layer to black-box machine-learning (ML) models. XAI improves model quality and resilience by detecting oversights, which can be addressed by the human in the loop. The rapid rise in the use of generative-AI models, which can have billions of parameters, will make traceability more difficult and expensive. Generative AI will require upskilling workers as review requirements become more complex and documentation standards (such as data health labels and model cards) become table stakes for governance.

— *Cloud migration, customer sentiment, and a shift toward pattern-based architecture move technology development teams to a secure-by-design model.* Businesses are increasingly expected to offer security, technology resilience, and other digital-trust functionalities as a core part of a product's value proposition. As a result, development teams are becoming more mindful of addressing security and technology risks earlier in the development and delivery life cycle (for example, by proactively identifying and self-remediating security defects during software development).

'Digital-trust technologies, such as trust architecture, digital identity, privacy engineering, and explainable AI, will quietly become integral to our lives. Consumers will rely on companies to use ever-evolving best practices to protect our data and digital dignity as well as be responsible stewards of the data they collect and use.'

– Liz Grennan, associate partner, Stamford

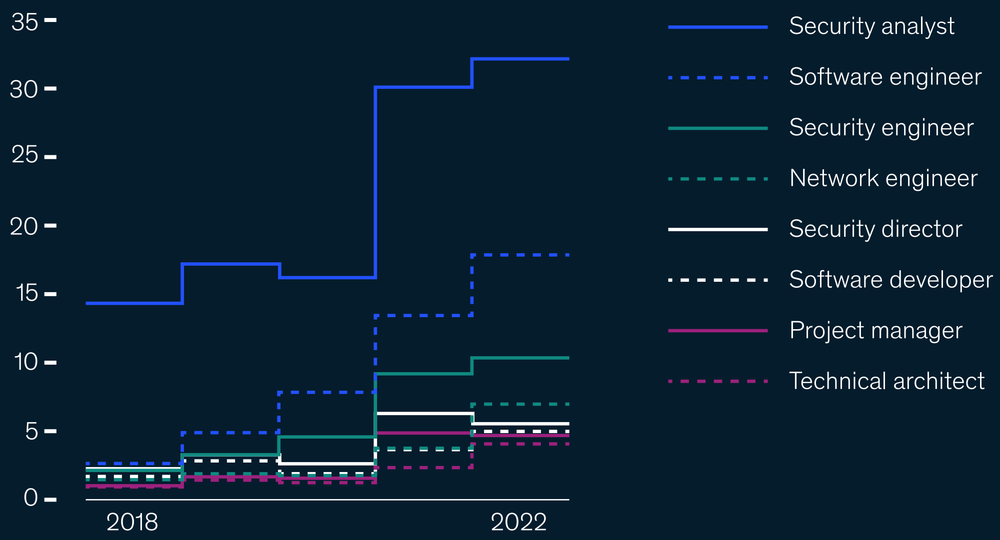
Talent market

Trust architectures and digital identity

Demand

Job postings increased by 16 percent between 2021 and 2022 and increased by an average of 39 percent between 2018 and 2022. While security analysts saw the highest demand between 2021 and 2022, demand for network engineers and software engineers experienced the highest growth rates.

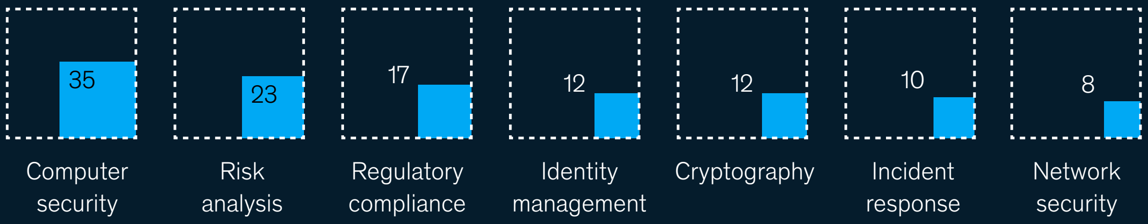
Job postings by title, 2018–22, thousands



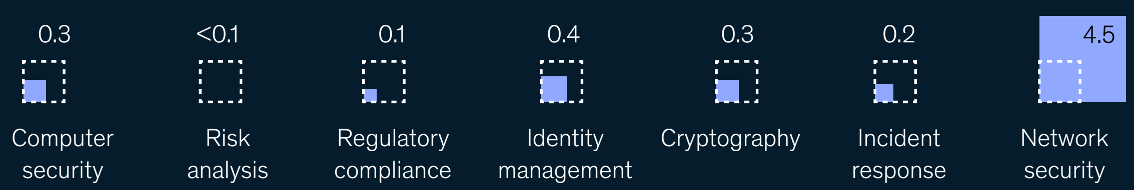
Skills availability

Computer security, risk, and regulatory compliance are the skills in highest demand. Specific branches of trust architecture, such as explainable AI, will require skills in specialized branches of ML.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



In real life

Real-world examples involving the use of trust architectures and digital identity include the following:

— Miami International Airport aims to implement biometric boarding at all gates by the end of 2023.[7] The project uses SITA's Smart Path, which leverages technology from NEC, to enable passengers boarding the plane to have their identity verified by camera. The system will create a faster and more seamless journey through the airport.

— In early 2023, the European Commission selected four consortiums of public and private organizations to lead pilot programs for the upcoming EU Digital Identity Wallet. The pilots will support eIDAS 2, an EU regulation that requires all EU member states to make a digital-identity wallet available to every citizen who wants one by 2024.[8]

— Netflix engineers developed Chaos Monkey, a novel way to ensure resiliency is being addressed. The software randomly terminates servers in production to ensure that engineers are architecting code in a way that would survive server failure.

— A bank used a black-box sales-lead-generation model, which hindered its adoption by relationship managers. Making the model explainable made the model output accessible to end users through standardized visualization and natural-language generation, which not only drove adoption but also enabled analysis of model weaknesses to help uncover systematic model errors and inform necessary improvements. Explainability also helped the banking company identify features that are needed to correctly predict samples in underrepresented groups, such as new clients, so that features are not excluded from the model.

— A top consumer-packaged-goods company was running into significant delays with its cloud migration program. To solve its issues, the organization implemented isolation zones, which allow enterprises to strategically control the boundaries, resources, policies, and segmentation of applications in their cloud deployments. This significantly enhanced technology resilience for the organization by preventing problems in one area from spreading to others and enabling a successful cloud migration. Similar concepts can be leveraged for privacy engineering. For example, isolation zones can be utilized to form General Data Protection Regulation (GDPR)—compliant segments, allowing for data storage and access only in the European Union.[9]

Underlying technologies

Digital-trust technologies include the following:

— *Zero-trust architecture (ZTA).* ZTA is an IT security design concept that assumes an organization's network is compromised by default and therefore enforces access decisions for every interaction with every entity.

— *Digital identity.* An identity consists of all the digital information that characterizes and distinguishes an individual or an entity. With self-sovereign identity (SSI), users control which identifying information to share and with whom. "Passwordless" identity allows users to verify and authenticate themselves not with traditional alphanumeric passwords but with alternatives such as

'"Secure by design"—inclusive of technologies such as zero-trust architecture as well as processes like shifted-left security—needs to become part of every company's normal approach to business in developing products. Customers expect that companies prioritize their security, privacy, and resilience as a core part of a product's value proposition.'

– Jim Boehm, partner, London

7 Tyler Choi, "Miami International Airport plans for biometric boarding at all gates by 2023," BiometricUpdate.com, May 17, 2022.
8 "European digital ID wallet—let's get prepared!" Thales, February 3, 2023.
9 Aaron Bawcom, Sebastian Becerra, Beau Bennett, and Bill Gregg, "Cloud foundations: Ten commandments for faster—and more profitable—cloud migrations," McKinsey, April 21, 2022.

biometrics, devices and applications, and documents. Businesses are developing “converged identity” solutions, which bring together different dimensions of identity into a single platform, enabling, for example, continuity as a person shifts from employee to business partner to customer.

— *Privacy engineering.* This practice governs implementation, operations, and maintenance of privacy by design. It focuses on the strategic reduction of privacy risks, enabling purposeful decision making about resource allocation, and effective implementation of privacy controls in information systems.

— *Explainable AI (XAI).* XAI covers methods and approaches that increase the transparency and interpretability of the inputs, weighting, and reasoning of ML algorithms, thus enhancing trust and confidence in them.

— *Technology resilience.* Technology resilience is the sum of practices and technical foundations necessary to architect, deploy, and operate technology safely across an enterprise environment. It includes components like immutable backup and self-healing networks. Such capabilities help organizations identify and overcome challenges like latency, outages, or data compromise and have the dual goal of reducing the likelihood of technology risk events and enabling faster recovery if a technology risk event does occur.

Key uncertainties

The major uncertainties affecting trust architectures and digital identity include the following:

— *Implementation complexity* is significant given resource requirements, talent scarcity, lack of shared taxonomies and aligned risk frameworks, coordination challenges across multiple parties, and required shifts in organizational norms and practices needed to achieve effective deployments.

— *Compatibility challenges* will be encountered when updating or migrating technologies and integrating them with legacy systems or with an abundance of fragmented point solutions.

— *Lack of standardization and widely accepted best practices* for how or when to use trust architecture techniques across industries will continue to be a challenge.

— *Tensions between privacy and fairness* or privacy and safety can arise (for example, tension between the avoidance of an excessive collection of demographic data and the need for such data to assess and mitigate bias or spot harms against minors).

— *There is no one-size-fits-all approach to decipher the black box of large AI models* to provide a meaningful explanation. As a result, solutions can be expensive and require a change in business process.

— *Many executive leaders still don’t prioritize digital-trust measures* (such as security, resiliency, explainability, and privacy) as core product functionality that should be considered from the start of a product life cycle as opposed to “on top work.”

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with trust architectures and digital identity:

— How do organizations manage higher customer, employee, and community expectations around security, experience (for example, frictionless login), and privacy by design?

— How will regulators reconcile past standards governing data privacy, data permanency, and other issues with the capabilities and requirements of new trust technologies? How can regulators be increasingly proactive in a rapidly evolving threat and technology landscape filled with complexity?

— What are the most critical systems and data types, and where are organizations typically exposed to risk? How can organizations be comfortable that they are sufficiently protected in line with the organization’s risk appetite, especially as data are exposed in the cloud and contract workers become more prevalent?

— How can organizations embed leading concepts such as zero trust into all developments in their digital organization to future-proof security?

Web3

The trend—and why it matters

Web3 goes beyond the typical understanding of cryptocurrency investments—it more significantly refers to a future model for the internet that decentralizes authority and redistributes it to users, potentially giving them increased control over how their personal data are monetized and stronger ownership of digital assets. In addition, it provides a range of possible commercial opportunities: new business models governed by decentralized autonomous organizations (DAOs) and enabled by eliminating intermediaries through secure (smart contract) automation, new services involving digital programmable assets, and new data storage and governance using blockchain technology. Web3 has attracted large pools of capital and engineering talent, but new ventures are still testing and scaling viable business models, and incumbent businesses continue to explore the best Web3 use cases. Early adopters face several challenges, including unclear and evolving regulations and immature and emerging technology platforms, often with a poorer user experience than existing Web2 utilities. However, companies are beginning to find success with Web3 pilots, including new user engagement models and financial-product offerings.

Web3

Scoring the trend
Momentum in Web3 has increased significantly across most dimensions since 2018.

Adoption rate score, 2022

Equity investment, 2022,
$ billion

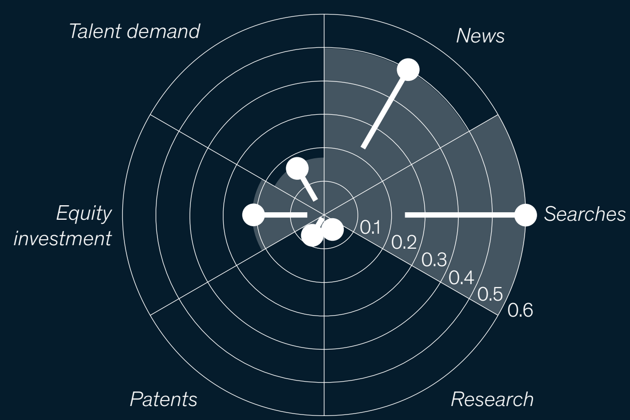
62

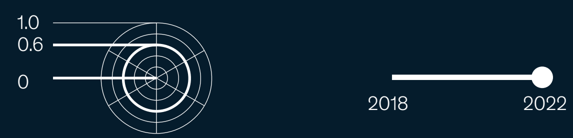
Job postings, 2021–22,
% difference

+40

Industries affected: *Financial services; Information technology and electronics; Media and entertainment; Retail*

Score by vector (0 = lower; 1 = higher)





Talent demand Ratio of actual skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

These are some recent developments involving Web3:

— *Some areas of Web3 experience downturns while others continue to soar.* The crypto market saw its market capitalization fall more than 50 percent in 2022 amid declining token value of several currencies and the closure of multiple crypto exchanges.[10] However, several other industry metrics in Web3 remained strong. In 2022, there was a 68 percent increase in nonfungible-token (NFT) sales count,[11] 87 percent growth in Ethereum core tool downloads,[12] more than 50 percent growth in on-chain stablecoin payment volume, and a 60 percent increase in active users of Web3 gaming.[13] Concurrently, the global tokenization market size, enabling conversion of assets into unique units, grew by about 23 percent.

— *The talent pool of new developers keeps growing.* Developers remain enthusiastic about Web3 despite declines in the crypto market. The number of monthly commits to open-source Web3 projects more than doubled over the course of 2022 as compared with 2018.[14] Additionally, there has been a steady 60 percent increase in active developers from the start of the 2020 bull run through the end of 2022.

— *Technology continues to improve and advance.* In recent years, the underlying technology in Web3 has improved and has seen an increase in adoption; as of 2023, there are thousands of decentralized applications currently running, compared with about a thousand in 2018.[15] Additionally, 2022 saw the progression of new technologies such as "zero knowledge" systems, which can prove a statement without providing additional information and have the potential to unlock blockchain scalability and new use cases (that is, increased privacy).

— *Regulatory activity ramps up.* The US Congress has proposed more than 50 crypto regulations, and several other countries are increasingly watchful of the crypto space after the closure of multiple crypto exchanges and loss of token value in 2022.[16] Many major economies have in place or have proposed digital-asset classifications, licensing requirements, and investment limitations, and government agencies have increased oversight over Web3 players. In 2023, the US Securities and Exchange Commission (SEC) initiated legal proceedings against major cryptocurrency platforms such as Coinbase and Binance, claiming most digital assets are securities. In parallel, the US House Financial Services Committee issued a draft bill that would create more clarity on what makes a digital asset a security as opposed to a commodity, where the majority of market capitalization would likely be deemed commodities.

— *A transition to sustainability begins.* Given the high energy consumption of older systems based on proof of work (PoW), transitions to more energy-efficient alternatives based on proof of stake (PoS) have progressed. One notable example is "the merge" in 2022, where Ethereum saw a live transition from PoW to PoS, making it more than 100 times more energy efficient.[17] In addition, bitcoin miners (which still use PoW) are increasing the share of renewable energy they consume to run the consensus algorithm.[18]

'Practical, recognizable applications of Web3 that deliver new revenues or material cost savings—such as tokenization of cash, financial and illiquid assets, or swaps and lending via smart contracts—are the priority. Making these appear familiar to investors is helping expand the market and is facilitating due consideration by regulators.'

– Matt Higginson, partner, Boston

[10] "Global cryptocurrency market cap charts," CoinGecko.
[11] "Average number and value of completed NFT sales on the Ethereum blockchain up to November 29, 2022," Statista.
[12] *Alchemy blog*, "Web3 development report (Q4 2022)," January 17, 2023.
[13] Zeynep Geylan, "Gaming unique active wallets grew 60% in 2022—on-chain transactions up 37%," *CryptoSlate*, January 27, 2023.
[14] Based on open-source repositories and code commits from GitHub.
[15] *Web3 Developer Report: Q3' 2022: Ethereum ecosystem and beyond*, Alchemy Insights, October 13, 2022.
[16] Jason Brett, "Congress has introduced 50 digital asset bills impacting regulation, blockchain, and CBDC policy," *Forbes*, May 19, 2022.
[17] Daren Matsuoka et al., "2023 State of Crypto report: Introducing the State of Crypto Index," a16z crypto, April 11, 2023; Ali Yahya, "What the merge means," a16z crypto, September 15, 2022.
[18] Alexander Neumueller, "A deep dive into Bitcoin's environmental impact," Cambridge University Judge School, September 27, 2022.

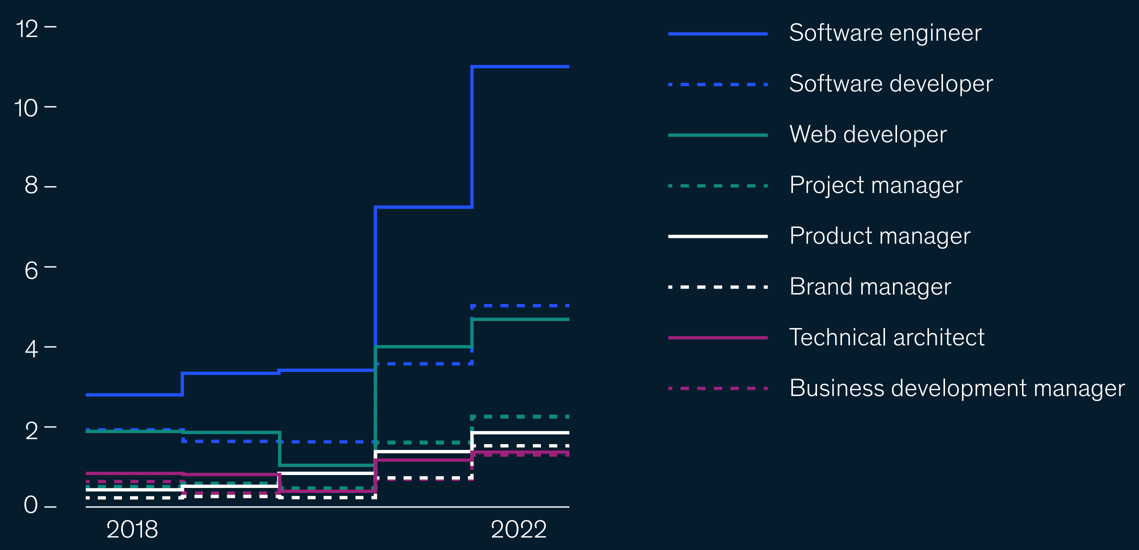
Talent market

Web3

Demand

Web3 job postings have grown more than fourfold since 2018, with the greatest growth occurring during 2021 and 2022. The outlook for future years, however, is less certain as Web3 companies navigate cryptocurrency volatility. Most job postings for Web3 are in software. Demand in this area has been growing rapidly and shifting geographically. In 2018, 40 percent of crypto developers were in the United States, but this fraction declined steadily to less than 30 percent in 2022.

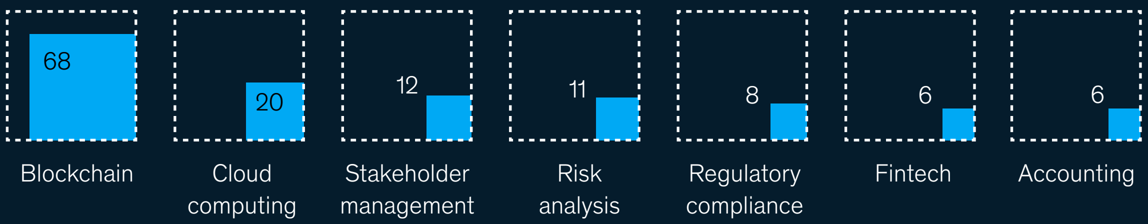
Job postings by title, 2018–22, thousands



Skills availability

Web3 organizations deal in a complex regulatory, legal, and accounting environment. Skills like risk analysis, stakeholder management, and regulatory compliance in the Web3 context are much more prevalent in job postings than in cited skills.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand

In real life

Real-world examples involving the use of Web3 include the following:

— In November 2022, JPMorgan Chase executed its first-ever on-chain cross-border blockchain transaction. The transaction involved tokenized Singaporean dollar and Japanese yen deposits and was executed on the Polygon blockchain. The trade is part of a larger partnership between JPMorgan Chase and DBS Bank called Project Guardian.[19]

— Securitize partnered with KKR to launch a tokenized fund (issued on the Avalanche blockchain) with exposure to KKR's Health Care Strategic Growth Fund (HCSG II). Tokenization opens up private equity to more individual investors by digitizing operations and lowering investment minimums.[20]

— 100 Thieves (100T), an esports and lifestyle brand, introduced NFTs to fans by simplifying onboarding and capitalizing on its rising brand profile. In celebration of its League of Legends championship win, 100T created a virtual diamond chain that allowed fans to freely claim it for 75 hours upon creation of a wallet on the 100T platform. More than 300,000 people redeemed the NFT—a majority were first-time wallet users.[21]

— After acquiring the Web3 studio RTFKT in 2021, Nike launched a Web3 platform called .Swoosh, which will offer Polygon-based NFT products to customers. The platform will serve as a hub for new product launches, as well as a medium for customers to cocreate and share virtual apparel designs.[22]

Underlying technologies

The foundational technologies that form the Web3 stack include the following:

— *Blockchain.* This is a digitally distributed, decentralized public ledger that exists across a computer network and facilitates recording of transactions.

— *Smart contracts.* Established in immutable code on a blockchain, these software programs are automatically executed when specified conditions (such as terms agreed on by a buyer and seller) are met.

— *Digital assets and tokens.* Examples of these digitally native intangible items include native cryptocurrencies, governance tokens, stablecoins, NFTs, and tokenized real-world and financial assets including cash.

Key uncertainties

The major uncertainties affecting Web3 include the following:

— *Regulation* is evolving as authorities choose approaches to governing issues such as consumer and investor protection, asset classification (for example, security, commodity, or currency) and its implications, legality and enforceability of blockchain-based contracts, accounting and tax standards, capital provisioning, accountability mechanisms, and know-your-customer and anti-money-laundering standards.

— *Value proposition* and user experience of Web3 compared with incumbent systems (which are also continuing to evolve) are often not fully understood. Even as platforms such as Reddit and Discord are beginning to experiment with Web3 solutions, the benefits remain unclear to many consumers and enterprises.[23]

[19] Brayden Lindrea, "JPMorgan executes first DeFi trade on public blockchain," *Cointelegraph*, November 3, 2022.
[20] "Securitize launches fund providing tokenized exposure to KKR fund for the first time in the U.S," Securitize, September 13, 2022.
[21] Kate Irwin, "Esports brand 100 Thieves gives out 300K Polygon NFTs—but won't call them NFTs," *Decrypt*, February 3, 2022.
[22] Andrew Hayward, "Nike launches .Swoosh Web3 platform, with Polygon NFTs due in 2023," *Decrypt*, November 14, 2022.
[23] Aaron Mak, "What is Web3 and why are all the crypto people suddenly talking about it?," *Slate*, November 9, 2021; Taylor Hatmaker, "NFTs and crypto wallets could be in Discord's future," *TechCrunch*, November 9, 2021.

— *Ecosystem infrastructure* is nascent and will continue to mature as business models (for example, merchants accepting digital loyalty tokens) and value chains (such as creation, trading, and secure storage of NFTs) are tested and refined or discarded.

— *Consumer protection* is increasingly becoming a focal point for regulators, especially amid recent failures of several nascent Web3 projects and fraud at major cryptocurrency exchanges.

— *Robustness of new technologies* that depend on code (for example, smart contracts) or data (for example, oracles) is improving but these technologies have experienced some notable failures. The composability of Web3 code could also perpetuate vulnerabilities in applications that currently are poorly understood.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with Web3:

— Which Web3 business models and value chains will emerge as technically reliable, scalable, and commercially viable? What will unlock mainstream adoption?

— As a cultural phenomenon, how will patterns of Web3 adoption vary among different populations?

— How will Web3 ecosystems coexist and interconnect with enterprise system architectures and with hyperscale Web2 platforms?

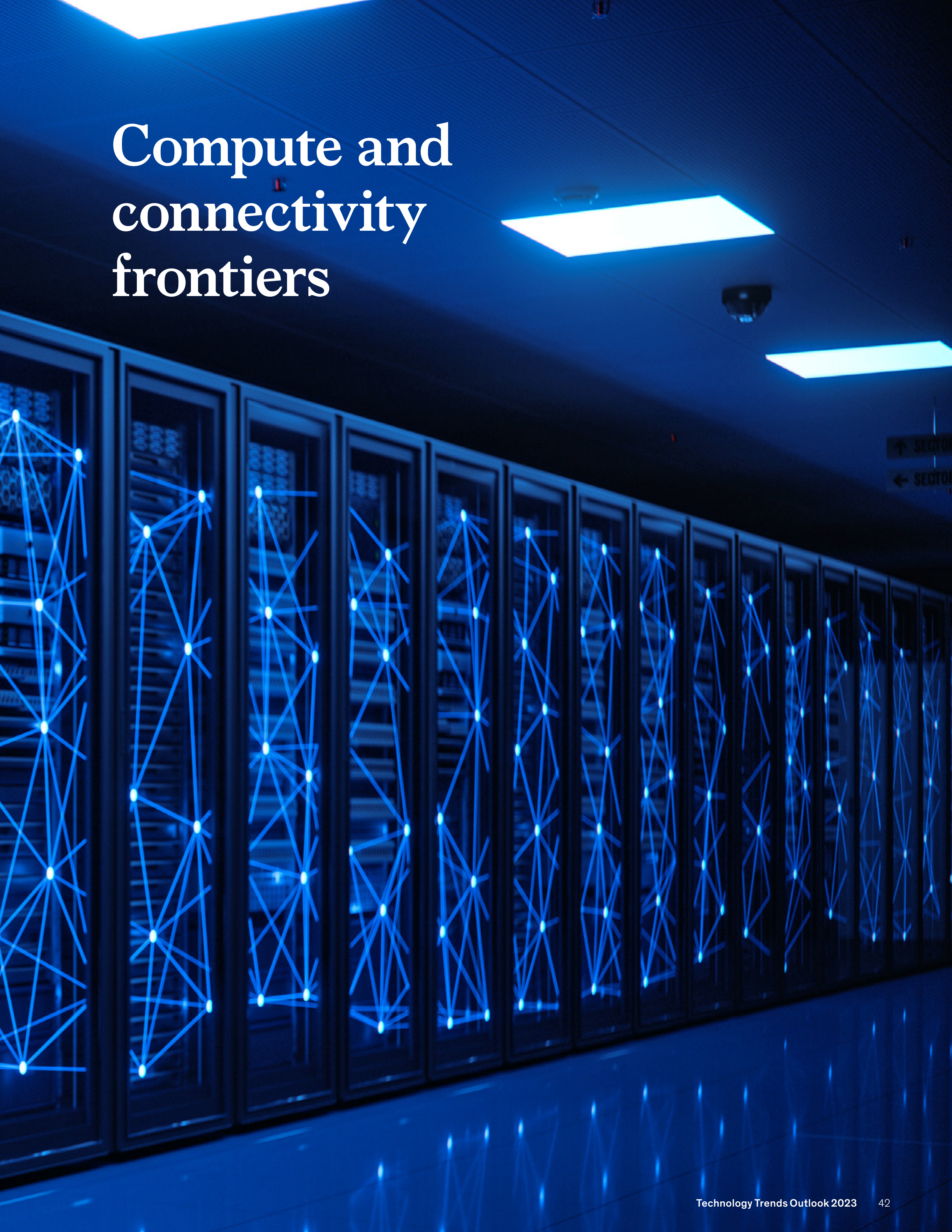
— How will regulatory action influence trust in Web3 and affect potential future innovation?

— How will Web3 and immersive reality enable new experiences in the metaverse?

‘While it’s clear that Web3 has had a difficult past 12 months, it’s hard not to be excited about the space, given all the developments. Particularly on the enterprise side, interest remains high, and companies are finally able to hire much-needed talent to further advance their offerings.’

– Ian De Bode, partner, Bay Area

Compute and connectivity frontiers



Advanced connectivity

The trend—and why it matters

Advanced-connectivity improvements will enhance user experiences for consumers worldwide and increase productivity in industries such as mobility, healthcare, and manufacturing. Companies have been quick to adopt advanced-connectivity technologies that build on existing deployments and connectivity standards, but some of the newer technologies on the horizon, such as low-Earth-orbit (LEO) connectivity and private 5G networks, face obstacles that will need to be addressed to increase uptake.

Advanced connectivity

Scoring the trend

Momentum scores across the board for this trend have increased significantly since 2018, with searches and news experiencing the most growth.

Adoption rate score, 2022

Equity investment, 2022, $ billion

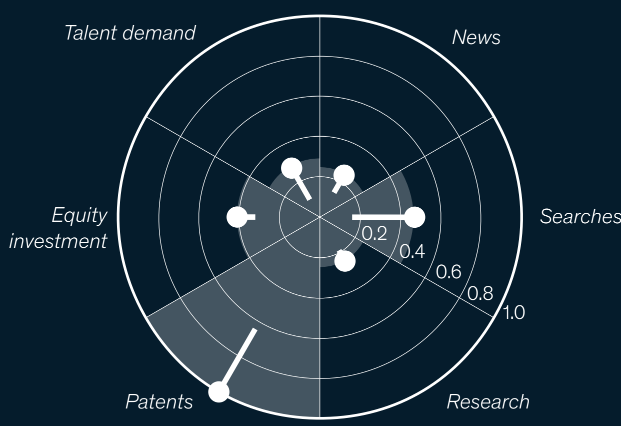
118

Job postings, 2021–22, % difference

+7

Industries affected: *Aerospace and defense; Automotive and assembly; Aviation, travel, and logistics; Construction and building materials; Electric power, natural gas, and utilities; Healthcare systems and services; Information technology and electronics; Media and entertainment; Metals and mining Oil and gas; Retail; Telecommunications*

Score by vector (0 = lower; 1 = higher)



Talent demand Ratio of actual skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

These are some recent developments involving advanced connectivity:

- *Integration of various connectivity technologies picks up.* With a variety of connectivity solutions (for example, Wi-Fi, cellular, and satellites) available for different use cases, attention is turning toward integrating them into a seamless customer experience. Major companies, such as Apple and T-Mobile, are investing in the integration of satellite connectivity into their existing products (for example, emergency SOS into the iPhone 14).

- *Telecom companies struggle to monetize 5G for consumers, and industrial applications grow slower than expected.* While APIs for 5G promise telecommunications companies the ability to monetize the delivery of 5G to consumers, adoption has been slow because consumer use cases relying on advanced connectivity have yet to scale. Many industrial companies chose to wait on the adoption of 5G private networks due to complexity, lack of understanding of cellular technology benefits and management, the cost of deployment, and the nascent state of end-to-end use cases. The 5G private-network market is picking up, and there are lighthouse deployments across various industries such as manufacturing, logistics, utilities, and a few others.

- *The fiber market grows and begins consolidating.* After the initial success of fiber networks in the 2010s, deal activity and company valuations have increased in the past few years. Several smaller fiber companies launched in recent years, but the market is now moving toward consolidation, with merger and acquisition activity increasing significantly, especially in Europe.

‘Unlocking the value of advanced connectivity is an ecosystem question. In the best case, it will be a virtuous circle where low-latency use cases, such as augmented reality, play a big role to drive demand, incentivize operators to push capacity network investments, and promote adoption of edge compute infrastructure. This, in turn, would drive more use cases, and the cycle would repeat.’

– Martin Wrulich, senior partner, Vienna

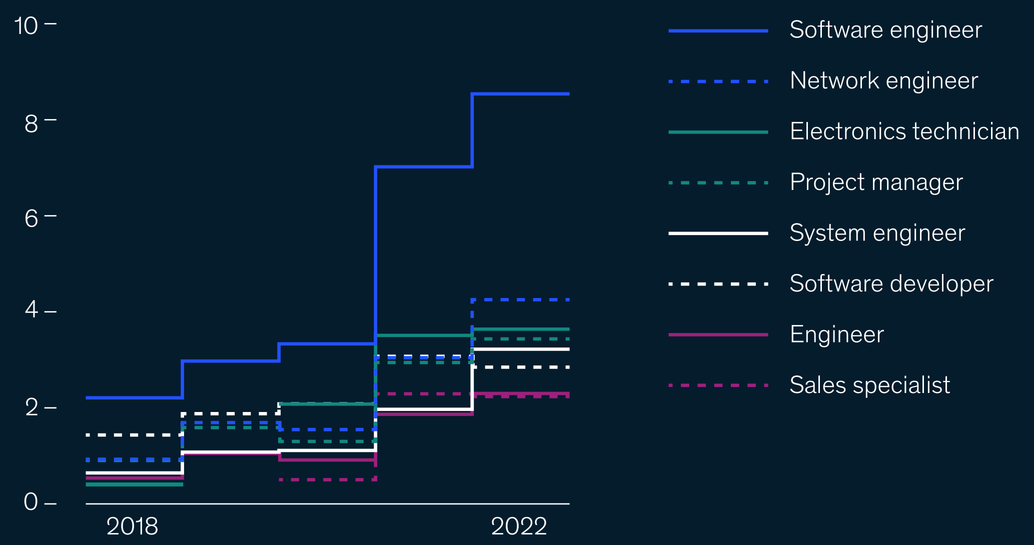
Talent market

Advanced connectivity

Demand

To realize the value of advanced connectivity, companies need technical talent, such as a variety of specialized engineers, to deploy the technologies at scale. The majority of new job postings in advanced connectivity are in software, network engineering, and electronics. Nontechnical roles such as project managers and sales specialists are also more heavily represented than in other tech trends

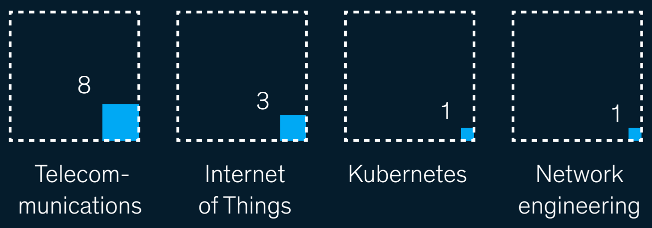
Job postings by title, 2018–22, thousands



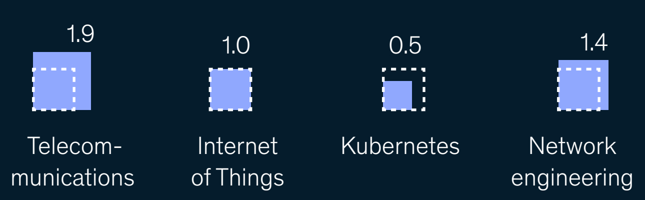
Skills availability

Typical telecommunications skills—such as network and spectrum design, network engineering, and network maintenance—are more available (albeit, in a tight market) than skills for network innovation (for example, developing open radio access networks, network functions virtualization, and Kubernetes) and the Internet of Things (IoT) (for example, developing applications, platforms, and APIs).

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



In real life

Real-world examples involving advanced connectivity include the following:

— In the Ericsson USA 5G Smart Factory, the company used next-generation connectivity devices to monitor the factory building's energy output and reduce energy use. Additionally, devices were connected wirelessly to Ericsson's network, making it easy to add and remove capacity in response to changing demand.

— Nokia collaborated with the Finnish Environment Institute (SYKE) to monitor the blue-green algae in the Baltic Sea. A drone is used to collect surface video in search of the algae and transmit the data back with 5G to enable real-time analysis and computer vision.

— Apple's more than $450 million investment in Globalstar and other satellite providers allows it to offer emergency satellite coverage for its iPhone 14. Customers with an iPhone 14 can use this feature to contact help in remote areas. It has already made the news for saving people in dangerous situations.

— A partnership between Centrica Storage and Vodafone aims to build a futuristic gas plant equipped with 5G infrastructure to enable automation and monitoring of key maintenance and engineering operations to reduce costs and increase plant efficiency.[24]

— Samsung is collaborating with telecom company O2 and the National Health Service in England to test smart ambulances that are equipped with 5G technology so paramedics can provide better and faster service to patients by using new features such as real-time video technology.

Underlying technologies

The noteworthy technologies in advanced connectivity include the following:

— *Optical fiber.* Physical strands of glass provide the most reliable high-throughput, low-latency connectivity.

— *Low-power, wide-area networks.* These wireless networks (for example, narrowband IoT, LTE-M, LoRa, Sigfox) can support a high number of connected devices.

— *Wi-Fi 6 and 7.* Next-generation Wi-Fi (also called industrial Wi-Fi) offers higher throughput, more controllable quality of service, and a cellular-like level of security.

— *5G/6G cellular.* These next-generation cellular technologies provide high-bandwidth, low-latency connectivity services with access to higher-spectrum-frequency bands capable of handling a massive amount of connected end points.

— *High-altitude platform systems (HAPS).* These are radio stations located at a fixed point 20 to 50 kilometers above Earth. HAPS can be deployed on lightweight aircraft to provide flexible capacity and access in remote locations.

— *LEO satellite constellations.* These offer wide-area coverage with significantly reduced latency compared with existing satellite offerings and can be used to provide coverage in remote areas, as well as serve as redundancy for mission-critical applications (for example, high-voltage electricity networks).

— *Direct-to-handset satellite connectivity.* Partnerships between telecom companies and satellite players allow direct access from phone to satellite, expanding network coverage beyond the reach of traditional cellular towers.[25]

[24] Nicola Brittain, "5G use cases: 31 examples that showcase what 5G is capable of," 5Gradar, September 9, 2021.
[25] Ivan Suarez, "The coming era of satellite direct-to-handset connectivity," Access Partnership, November 28, 2022.

‘There has been a lot of interest from industrial verticals in next-generation connectivity benefits, and the largest infrastructure and telecom and tech players are making massive investments. However, there is still a lot of work to be done by a wide number of ecosystem players to compile a very complex tech stack that enables advanced use cases to scale.’

– Zina Cole , partner, New York

Key uncertainties

The major uncertainties affecting advanced connectivity include the following:

— *Business viability* remains in question as price wars, commoditization of connectivity, telecom companies’ struggle in monetizing better network quality, and ever-growing traffic and cost of deployment has led to consistently decreasing returns on investment for telecom companies globally.

— *Availability* depends on the maturation of use cases, such as 5G-enabled robotics and gaming on the go, for industrial verticals and consumers requiring higher service-level agreements such as high throughput or low latency.

— *Key uncertainties of advanced-connectivity* adoption vary by technology. For example, ecosystem maturity plays a critical role in adoption of IoT, whose uptake has been slower than expected due to a highly fragmented market, security concerns, interoperability, complex deployments involving a vast variety of players, and a lack of standardization. For 5G and 6G, telecom operators’ monetization struggles might affect their ability to build necessary infrastructure for at-scale rollouts globally.

— *Government involvement* is still unfolding and will play a role in terms of regulations and funding for 5G and next-generation digital infrastructure.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with advanced connectivity:

— How will changes in the fiber market (for example, financing and acquisitions) affect network options for customers? Will 5G be sufficiently monetized?

— How will companies respond to the long tail of smaller fiber operators in the market—for example, acquire, partner, avoid, or build potentially redundant networks alongside existing ones?

— What are the expectations from various stakeholders for next-generation wireless technologies?

— What will 6G look like? What needs to happen to make 6G a success?

— Will private-network adoption finally take off? What do industrial verticals need to know about it to avoid missing out on its benefits?

— What are the key levers to speed up IoT adoption?

Immersive-reality technologies

The trend—and why it matters

Immersive-reality technologies use spatial computing to interpret physical space; simulate the addition of data, objects, and people to real-world settings; and enable interactions in virtual worlds with various levels of immersion provided by augmented reality (AR), virtual reality (VR), and mixed reality (MR). Venture capital investors provided about $4 billion of funding in AR and VR start-ups in 2021, the second-most-successful funding year after 2018. Although total investments in AR and VR subsequently declined in 2022, investors showed continued interest in the trend: at least seven investment rounds of $100 million or more closed last year.[26] Our research suggests that the emerging metaverse could generate up to $4 trillion to $5 trillion in value across consumer and enterprise use cases by 2030.[27]

Immersive-reality technologies

Scoring the trend

While interest and investment levels have held steady in the past several years, innovation and demand for talent have been on the rise.

Adoption rate score, 2022

0 1 2 3 4 5

None Mainstream

Equity investment, 2022,
$ billion

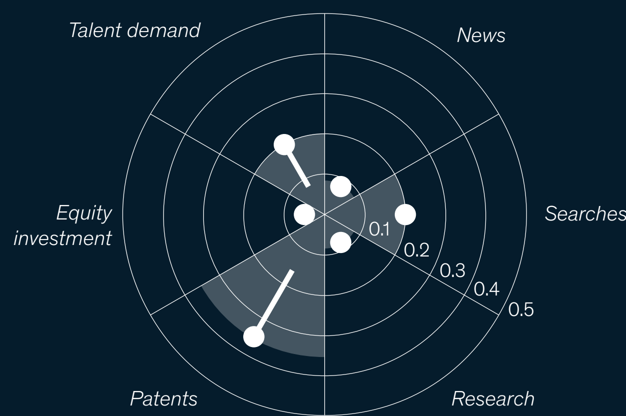
16

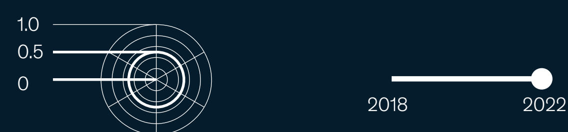
Job postings, 2021–22,
% difference

+10

Industries affected: *Aerospace and defense; Automotive and assembly; Aviation, travel, and logistics; Construction and building materials; Consumer packaged goods; Education; Electric power, natural gas, and utilities; Healthcare systems and services; Information technology and electronics; Media and entertainment; Real estate; Retail*

Score by vector (0 = lower; 1 = higher)





Talent demand Ratio of actual skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

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[26] Joanna Glasner, "VR/AR funding stalls as metaverse mass adoption still not reality," Crunchbase, November 4, 2022.

[27] McKinsey research suggests that the metaverse could generate up to $5 trillion in value across consumer and enterprise use cases by 2030; *Value creation in the metaverse*, McKinsey, June 2022.

Latest developments

These are some recent developments involving immersive-reality technologies:

— *Declines in investment and consumer adoption of VR and AR devices signal a tempering, but adoption of AR on flat devices rises.* Investments in immersive-reality technologies spiked in 2021, with $14 billion investment in 2018, $32 billion in 2021, and $16 billion in 2022.[28] In tandem, consumer adoption slowed, with worldwide shipments of VR headsets and AR devices declining more than 12 percent in 2022 after 2021 saw increased sales of home-entertainment devices during the pandemic lockdown and increased inflationary pressures in 2022 tempered consumer spending.[29] However, use of AR on flat devices (for example, phones) continues to rise: the installed base of AR apps increased from 1.03 billion in 2016 to 6.06 billion by 2022.[30]

— *New devices continue to hit the market.* Although hardware innovation took a dip, new VR headsets were released in 2022. New VR headsets are also expected throughout 2023, and peripheral devices (for example, haptics and displays) continue to advance, with new user-experience innovations anticipated to bolster the consumer market. So far in 2023, PlayStation has released its VR2 headset—which has high potential for adoption by tapping into the large existing PlayStation user base—and HTC has released its Vive XR Elite headset for the high-end consumer and professional segment to positive reviews.

— *Announcements signal technical leaps in future devices.* Apple announced the 2024 release of its Vision Pro AR/VR headset, which will feature technology such as eye tracking, hand-gesture recognition, and seamless scrolling. Apple supported Vision Pro with an enormous base of talent and capital and fortified it with more than 5,000 patents. The company believes the headset could offer notable advantages and aspires to set new standards in the realm of mixed reality.

— *Enterprise collaborations continue pushing the trend forward.* Investment in the enterprise segment has largely increased through partnerships. In August 2022, Lenovo, for instance, announced a collaboration with CareAR to deliver next-generation AR wearable solutions for field technicians.[31] Enterprise adoption is expected to continue rising even further as digital-twin use cases with the potential to improve efficiency across operating environments (for example, warehouses, clinical trials, and retail stores) emerge.

'While we may see fewer devices in the future after the near frenzy of the past one to two years, we'll continue to see rapid innovation of features and form factor in upcoming devices.'

– Hamza Khan, partner, London

[28] PitchBook investment data, 2018–22.
[29] Jonathan Vanian, "Metaverse off to ominous start after VR headset sales shrank in 2022," CNBC, December 28, 2022; "Global shipments of AR/VR headsets decline sharply in 2022 following the prior year's strong results, according to IDC," Business Wire, March 8, 2023; Mike Snider, "Two-thirds of Americans, 227 million, play video games. For many games were an escape, stress relief in pandemic," *USA Today*, July 13, 2021.
[30] "Consumer mobile device augmented reality applications (embedded/standalone) worldwide from 2016 to 2022 (in millions)," Statista.
[31] "CareAR and Lenovo collaborate to advance service experience management (SXM) for next generation enterprise extended reality (XR) solutions," PR Newswire, August 23, 2022.

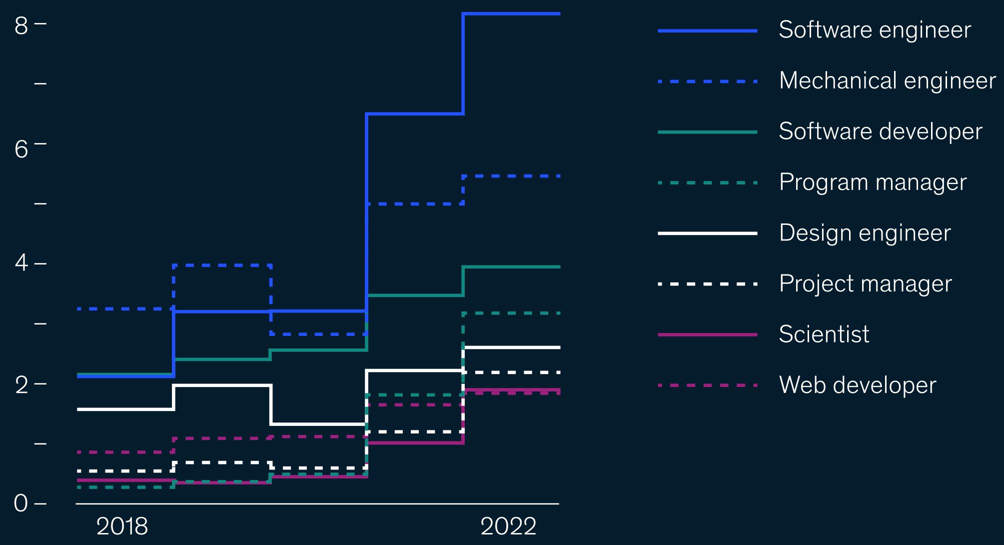
Talent market

Immersive-reality technologies

Demand

Immersive-reality job postings have more than doubled since 2020 and grew slightly between 2021 and 2022. This field brings together a wide range of technical, creative, and management professionals, with high job demand for software, hardware, design, program and project management, and scientists.

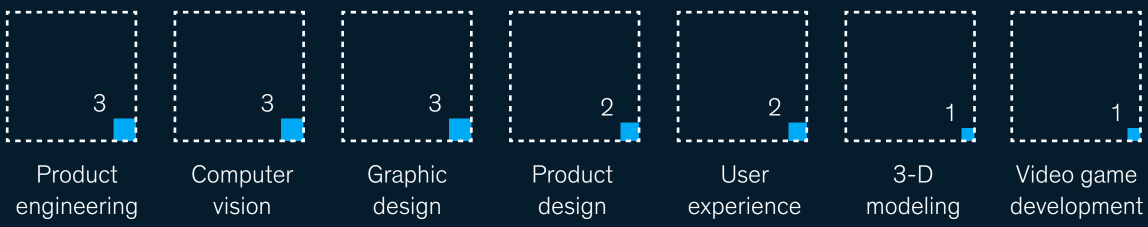
Job postings by title, 2018–22, thousands



Skills availability

While skills such as graphic design, computer vision, and 3-D modeling are more plentiful in the market, product design, product engineering, and video game development professionals are in shorter supply.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand

In real life

Real-world examples involving immersive-reality technologies include the following:

— Nike partnered with Roblox to launch Nikeland—a metaverse space recreating its headquarters with avatars featuring Nike products. The brand also released .SWOOSH to host community experiences in the metaverse and allow customers to purchase digital assets.[32]

— In September 2022, Lowe's unveiled the home-improvement retail industry's first interactive digital twin of a store, intending to enable better floor management and customer service by allowing store associates to visualize and interact with the full complement of a store's data.[33]

— When Morehouse College wanted to engage its remote students, biomolecular chemistry professor Muhsinah Morris introduced a virtual digital twin of the school's chemistry lab to enable students to conduct experiments just as they would in person.[34]

Underlying technologies

Immersive-reality technologies include the following:

— *Augmented reality.* AR enables partial immersion by adding information to real-world settings.

— *Virtual reality.* VR immerses users in entirely virtual settings.

— *Mixed reality.* MR enables a level of immersion between AR and VR, adding virtual elements to the real world so that users can interact with both.

— *Spatial computing.* This type of computing uses the perceived 3-D physical space around the user as a canvas for a user interface.

— *On-body and off-body sensors.* These sensors detect objects and bodies for representation in virtual settings. They may be embedded in handheld or wearable devices or mounted around users.

— *Haptics.* These feedback devices convey sensations to users, usually as vibrations.

— *Location-mapping software.* This software integrates real-time user physical location and surroundings into AR to provide an overlay of the surrounding physical environment in the virtual environment.

'Immersive experiences and real-time 3-D continue to grow; we expect them to become the predominant way we experience the internet over the next decade. Adoption thus far has been led by gaming; however, we continue to see expansion into other consumer and enterprise use cases, such as collaboration and high-precision training. Massive amounts of innovation across the underlying infrastructure, platforms, AI, devices, and experience layers continue to move fast. The critical technology pieces will start to come together over the next few years.'

– Shivam Srivastava, partner, Bay Area

[32] Jessica Golden, "Nike teams up with Roblox to create a virtual world called Nikeland," CNBC, November 19, 2021; Tyler Warner, "Everything you need to know about Nike's .SWOOSH," Lucky Trader, November 15, 2022.
[33] "Lowe's unveils industry-first digital twin, giving associates 'superpowers' to better serve customers," Lowe's, September 20, 2022.
[34] Nick Clegg, "How the metaverse can transform education," Meta, April 12, 2023.

Key uncertainties

The major uncertainties affecting immersive-reality technologies include the following:

— *Device improvements in hardware and software are needed,* particularly for AR devices, to enable miniaturization and weight reduction, make devices more durable, improve sensor precision, increase user comfort, reduce heat output, and extend battery life.

— *The pace and level of cost reductions remain uncertain* but will be needed to make applications more consumer-friendly and scalable.

— *Growth in the breadth of user needs is still in question.* The metaverse is likely a few years away from a true tipping point where demand grows from targeted niche needs to broader mass-market customer usage. Certain business-focused considerations, including how end-consumer price points evolve, will also impact the pace of adoption.

— *Mitigating security and privacy concerns* related to tracking user behavior will be critical to building trust.

— *Safety concerns are also paramount* when considering usage of vision-limiting AR and VR platforms outside of highly controlled environments.

— *End-user devices* could take multiple forms depending on intended usage, from independent AR and VR platforms to peripheral AR accessories for mobile phones. Additionally, other devices, such as flat screens that display immersive experiences, are currently gaining faster adoption than AR/VR, indicating the device can have an impact on momentum.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with immersive-reality technologies:

— Will immersive reality shift the new wave of (remote) work?

— Will initial ideas start to break through to scale? What will be the triggers for breakout success?

— How will enterprises effectively manage the tech infrastructure required for new and evolving consumer use cases?

Cloud and edge computing

The trend—and why it matters

In the future, enterprises will leverage an infrastructure footprint that involves compute and storage at multiple location points, from on-premises to closer-to-premises (the edge) and from small regional data centers to remote hyperscale data centers. Edge computing provides flexibility for organizations to process data closer to their origins faster (ultra-low latency) and achieve data sovereignty and enhanced data privacy as compared with cloud, which can unlock a variety of new use cases. Reduced distance to end users will shrink data transmission delays and costs, as well as provide faster access to more relevant sets of data, which helps companies comply with data residency laws. Public cloud will continue to play a critical role in the enterprise of the future by performing non-time-sensitive computing use cases at much better economies of scale. Ongoing integration of cloud and edge resources will let users extend the innovation, speed, and agility of cloud to edge and real-time systems, thereby accelerating innovation, lifting productivity, and creating business value.

Cloud and edge computing

Scoring the trend

Cloud and edge computing have become core technologies for many digital solutions, with levels of interest increasing across multiple facets from 2018 to 2022.

Adoption rate score, 2022

0 1 2 3 4 5

None Mainstream

Equity investment, 2022, $ billion

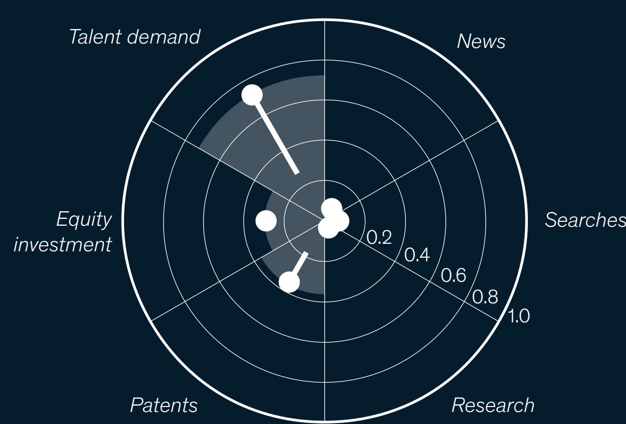
84

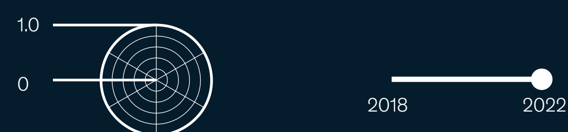
Job postings, 2021–22, % difference

+12

Industries affected: *Aerospace and defense; Automotive and assembly; Aviation, travel, and logistics; Chemicals; Electric power, natural gas, and utilities; Financial services; Healthcare systems and services; Information technology and electronics; Manufacturing; Media and entertainment; Pharmaceuticals and medical products; Retail; Telecommunications*

Score by vector (0 = lower; 1 = higher)





Talent demand Ratio of actual skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

These are some recent developments involving cloud and edge computing:

- *The rate of migration slows.*[35] Ballooning costs, as well as data privacy and latency-related issues, have contributed to the slowdown, though enterprises continue migrating to public cloud. In some situations, however, enterprises are "repatriating" from cloud. A recent study from the Uptime Institute Global Data Center found that approximately 33 percent of respondents had repatriated from the cloud to a data center or co-location facility. Of those that repatriated, however, only 6 percent abandoned the cloud altogether. The majority engage in a hybrid approach, using on-premises and public-cloud options.[36]
- *Edge computing continues to attract investment.* More than 400 edge use cases across various industries have been identified, and edge computing is projected to see double-digit growth globally over the next five years.[37] Edge adoption is on the rise for a variety of reasons, including a lack of reliable connectivity in certain locations (for example, remote factories). Through edge computing, data can be processed where they are created, allowing business decisions to be made with efficient data analysis at higher speeds and accuracy.[38]
- *Cloud use in high-performance compute and AI/ machine learning (ML) picks up.* To capitalize on the growth of these workloads and optimize their hardware, cloud providers are not only relying on partnerships but also investing in in-house silicon design (for example, Google's tensor processing units and Amazon Web Services' Nitro System).
- *Hyperscalers increasingly focus on sustainability.* Google announced a complete transition to 24/7 carbon-free energy by 2030, and Microsoft made a commitment to a 100 percent renewable-energy supply by 2025.

'As companies move from a cloud-first to cloud-smart approach, they see edge as a complement to cloud and are getting more nuanced in how they approach the decision of where to host each workload. The mantra now is "do not sleep on the edge, because if you snooze, you lose!" Embrace edge tomaintain your edge.'

– Bhargs Srivathsan, partner, Bay Area

35 Lindsay Clark, "Oh dear, AWS. Cloud growth is slowing as customers get a dose of cost reality," *The Register*, January 19, 2023.
36 Owen Rogers, "High costs drive cloud repatriation, but impact is overstated," Uptime Institute, March 22, 2023.
37 "New IDC spending guide forecasts edge computing investments will reach $208 billion in 2023," IDC, February 15, 2023.
38 Stephen J. Bigelow, "What is edge computing? Everything you need to know," TechTarget, updated December 2021.

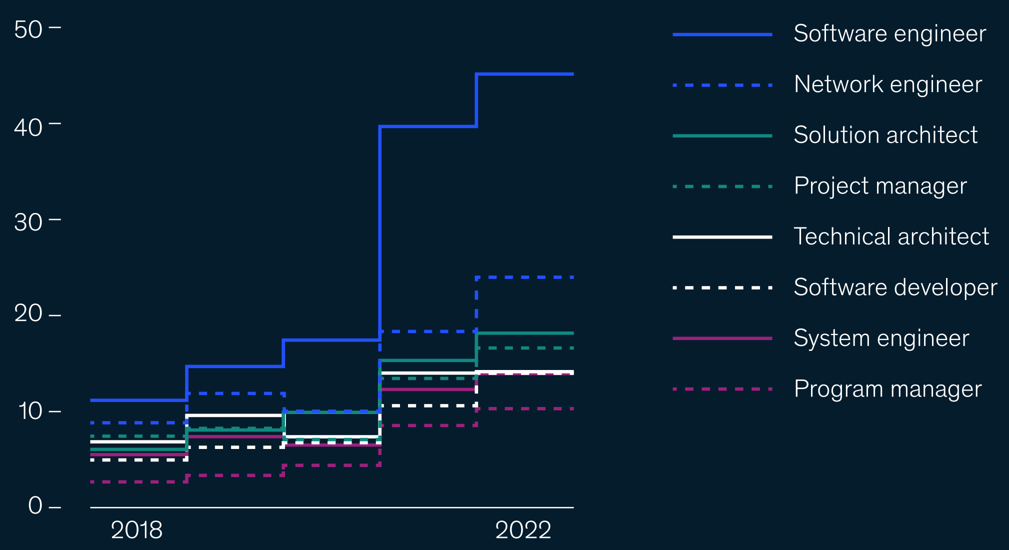
Talent market

Cloud and edge computing

Demand

After staying nearly flat from 2018 to 2020, cloud jobs saw a significant increase in 2021 but grew at a slower pace in 2022. Cloud and edge job postings were particularly high for software engineers and network engineers, while nontechnical project and program roles grew moderately relative to 2021.

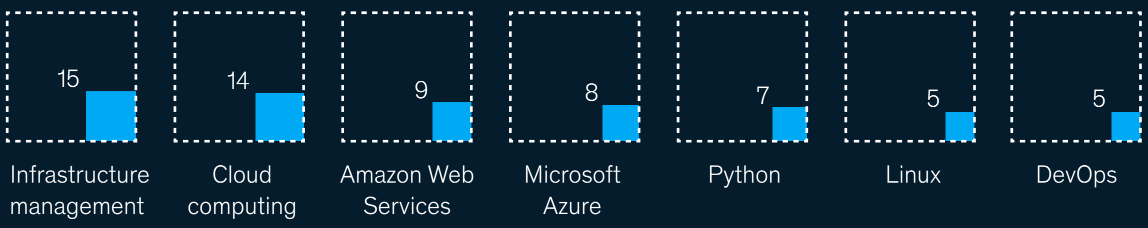
Job postings by title, 2018–22, thousands



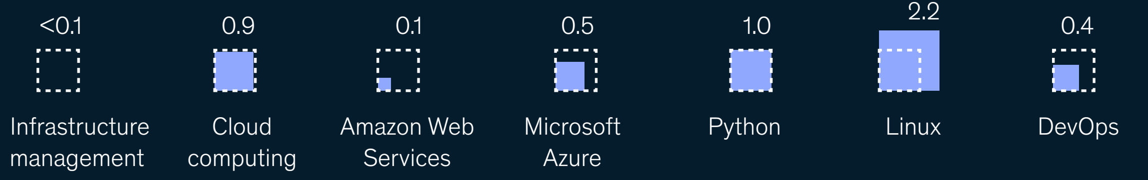
Skills availability

Most of the technical skills required for cloud computing, such as DevOps, Kubernetes, and Terraform, are in relatively short supply.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



In real life

Real-world examples involving cloud and edge computing include the following:

— Baxter, a medical-device manufacturer, has avoided hundreds of hours of unplanned machine downtime by adopting a proactive maintenance strategy powered by an AI-based end-to-end solution hosted on edge computing devices.

— Aramco uses edge-powered computer vision solutions to enhance safety, provide proactive monitoring for equipment failure, and enable automation of drilling equipment and processes for its offshore drilling rigs.

— Wildlife conservation efforts in Africa use the Internet of Things (IoT) and edge computing technologies to monitor the movements of rhinoceroses and detect the presence of poachers over large areas of land, such as the Hluhluwe-Imfolozi Park in South Africa.

— Owing to growing demand, cloud providers have made efforts to optimize hardware for AI and ML workloads. In October 2022, Oracle expanded collaboration with Nvidia to bring the full Nvidia accelerated computing stack to Oracle Cloud infrastructure. In November 2022, Microsoft announced a multiyear collaboration with Nvidia to build one of the most powerful cloud AI supercomputers in the world.

Underlying technologies

We see edge being deployed in various formats, depending on proximity to the user or data generated and scale of resources involved.

— *IoT or device edge.* IoT devices such as sensors and video cameras are used to collect and process data from their sources. These devices often come with basic computing and storage capabilities.

— *On-premises or "close to the action" edge.* These are computing and storage resources deployed within the premises or at a remote or mobile location where data are being generated.

— *Operator, network, and mobile edge computing (MEC).* These are private- or public-computing and storage resources deployed at the edge of a mobile or converged-services provider's network, typically one network hop away from enterprise premises.

— *Metro edge.* Data centers with smaller footprints (for example, about three megawatts) located in large metro areas augment public cloud with near-premises computing power and storage to provide lower latency and/or higher availability.

Key uncertainties

The major uncertainties affecting cloud and edge computing include the following:

— *Scaling hurdles could arise* as the number of edge nodes and devices grows because edge computing does not benefit from the same economies of scale as traditional cloud computing.

— *Other challenges include lack of ROI visibility,* an overall longer path to returns for edge development, lack of customer understanding of value-add use cases, large investment requirements for scaling from pilot to at-scale implementations, near-term oversupply of edge compute locations, a complicated technical stack requirement (especially due to integration with the existing tech landscape at most companies), and a lack of ready-to-deploy solutions.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with cloud and edge computing:

- Will flexibility and positioning in a business and regulatory sweet spot make edge more disruptive than cloud? Or will inhibitors such as lack of interoperability and commonality of standards in networking prevent edge from reaching its full potential?
- Will hyperscale cloud providers win the edge race, and how will telecommunications companies with 5G-enabled MEC contend or partner with hyperscalers?
- How will rapidly evolving AI technology and, importantly, accompanying regulatory changes alter cloud and edge provider business models?
- How will specialized chips deployed both in data centers and at the edge, such as AI inference or always-on sensors, modify the competitive cloud and edge landscape?
- Will the increase in number of storage and processing units lead to security vulnerabilities?
- As data centers transition to green IT measures and as the amount of critical infrastructure, number of devices, data centers, and related energy requirements increase, how will cloud and edge evolve in line with the sustainable IT paradigm?
- As sensor costs drop and their performance increases, how will edge and cloud resources cope with growing demand for data movement and AI-enabled analytics?

'The demand for edge computing is expected to increase significantly over the next few years, and use cases requiring edge capabilities will multiply. This may create opportunities for a number of technology providers currently playing only marginally in the public cloud space to capture value by increasing edge capabilities now.'

– Andrea Del Miglio, senior partner, Milan

Quantum technologies

The trend—and why it matters

Quantum technologies promise to take advantage of the unique properties of quantum mechanics to perform specific types of complex calculations exponentially more efficiently than classical computers, secure communication networks, and provide a new generation of sensors capable of massive improvements in sensitivity over their classical counterparts. In principle, quantum technologies can perform simulations and solve problems that would lead to major advances across industries, including aerospace and defense, automotive, chemicals, finance, and pharmaceuticals. However, prospective users of quantum technologies should prepare for an uncertain adoption road map as technological challenges remain for the realization of fully error-corrected quantum computers and scalable quantum-communication networks.

Quantum technologies

Scoring the trend

Despite research advances made in the past few years, quantum technologies remain nascent and have garnered less attention than more mature technologies.

Adoption rate score, 2022

0 1 2 3 4 5

None Mainstream

Equity investment, 2022,
$ billion

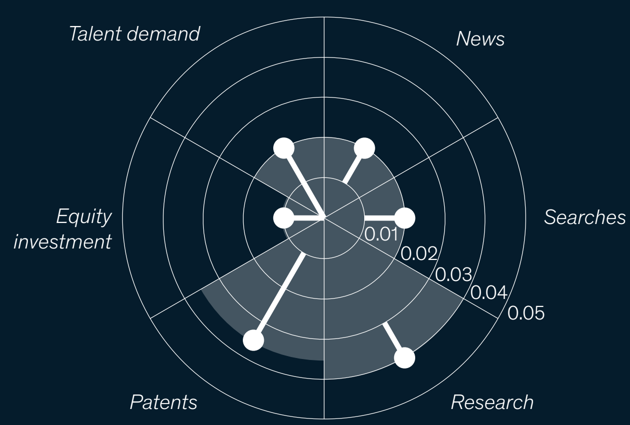
2

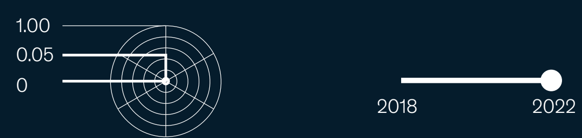
Job postings, 2021–22,
% difference

+12

Industries affected: *Aerospace and defense; Automotive and assembly; Aviation, travel, and logistics; Chemicals; Financial services; Information technology and electronics; Metals and mining; Oil and gas; Pharmaceuticals and medical products*

Score by vector (0 = lower; 1 = higher)





Talent demand Ratio of actual skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

These are some recent developments involving quantum technologies:

- *Hardware advancements continue.* In November 2022, IBM revealed Osprey, a 433-qubit quantum processor with more qubits than any of the company's previous quantum computers.[39] A few months earlier, Google announced the first experimental demonstration of reducing quantum error rates by increasing the number of physical qubits interacting to form a logical qubit. Many scientists believe this provides further evidence that errors can be reduced enough to enable quantum computers to perform large-scale computations.[40]
- *The talent gap remains significant but may be narrowing.* Adoption of quantum technologies could be hampered by a shortage of quantum experts who can build devices and solutions leveraging quantum technologies. However, 2022 saw a slight improvement: McKinsey research showed that nearly two-thirds of open jobs in the industry could be filled with new master's-level graduate degrees in quantum technologies, whereas in 2021, only about a third of those jobs could be filled. Going forward, the gap could narrow further: the number of universities offering quantum-technology master's programs nearly doubled in 2022.
- *The focus on information security increases.* In July 2022, after hosting a six-year competition, the National Institute of Standards and Technology (NIST) announced the first set of four quantum-resistant cryptographic algorithms. Meanwhile, papers published in 2022 indicated increasing risks to 2048-bit RSA encryption, and the number of qubits required to break RSA encryption has fallen by orders of magnitude since 2015. As quantum hardware and algorithms improve, players are investing in quantum key distribution (QKD) and postquantum security to keep data safe.
- *Quantum scientists win Nobel Prize in physics.* Quantum scientists Alain Aspect, John Clauser, and Anton Zeilinger won the 2022 Nobel Prize in physics for their 1970s and 1980s research on entangled photons. Their discoveries have applications for quantum communications, and several companies have since used similar techniques to transfer information securely.

'Given that we see algorithms improving and the numbers of qubits growing, organizations should think about adding additional protection to their sensitive and valuable data now. Bad actors could harvest data today and decrypt it with quantum computers later.'

– Mena Issler, associate partner, Bay Area

[39] "IBM unveils 400 qubit-plus quantum processor and next-generation IBM Quantum System Two," IBM press release, November 9, 2022.
[40] Rajeev Acharya et al., "Suppressing quantum errors by scaling a surface code logical qubit," *Nature*, February 22, 2023.

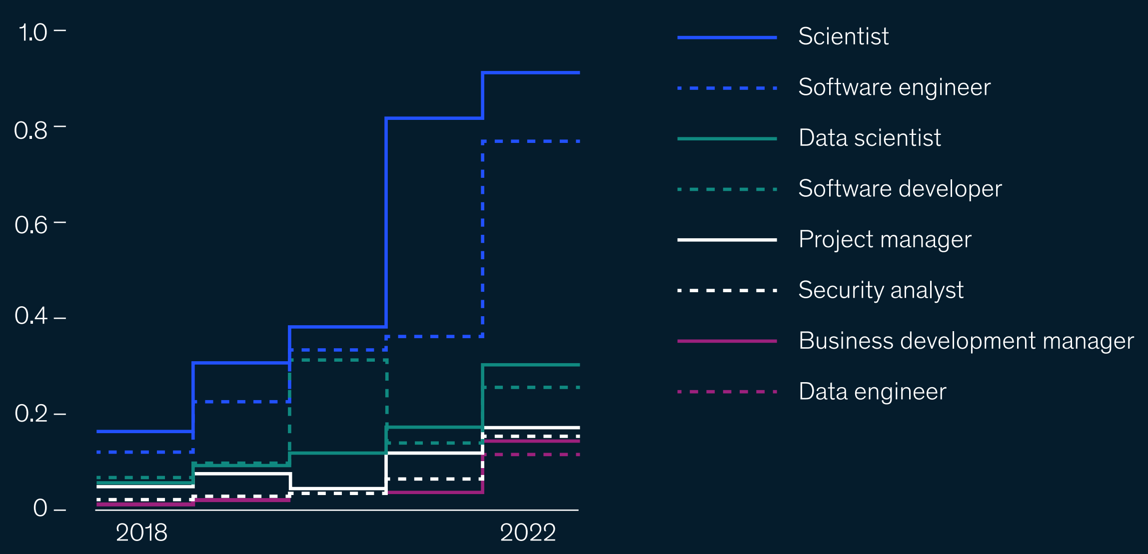
Talent market

Quantum technologies

Demand

While quantum technology has a small labor market, talent demand has grown fourfold since 2018. Given the nascency of the technology, there is a low number of graduates from quantum-specific programs. As a result, talent is sourced from the broader fields of physics, mathematics, electrical engineering, chemistry, biochemistry, and chemical engineering. Hiring in the field of quantum technology is increasing for applied roles, such as business development managers and data engineers. If the trend follows the path of more mature technologies, like AI, we may see the rise of specialized roles such as quantum-software engineers.

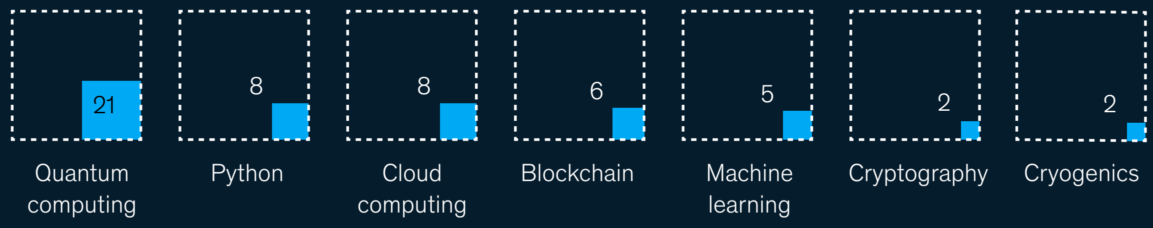
Job postings by title, 2018–22, thousands



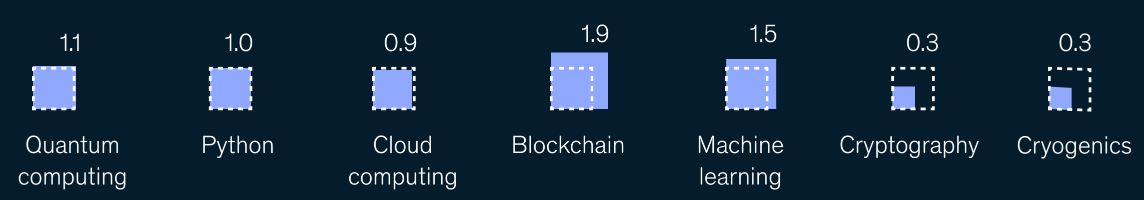
Skills availability

Although the total demand for quantum jobs remains low, the supply of skilled talent is even lower, with specialized skills such as cryptography and cryogenics in shortest supply.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



In real life

Real-world examples involving the use of quantum technologies include the following:

— JPMorgan Chase, Toshiba, and Ciena demonstrated the viability of a QKD network for metropolitan areas, enabling detection and defense against eavesdroppers. A QKD-secured channel on the network was used to deploy and secure a blockchain application by JPMorgan Chase.

— Researchers from Amazon Web Services (AWS) implemented a point-to-point quantum-secured network in Singapore. The team connected two QKD devices using a production-grade optical-fiber network.

— In early 2022, Robert Bosch, a major sensor developer, announced the formation of an internal division devoted to developing and commercializing quantum-sensing technologies. The in-house start-up will use the results of existing quantum research to create new products, with medical applications possible.[41]

— Quantum Computing Inc (QCi) solved a German automotive OEM's complex design challenge in record time (six minutes). The challenge was a 3,854-variable optimization problem to configure sensors for a given vehicle so they would provide maximum coverage (that is, detect obstacles in different driving scenarios) at minimum cost.

Underlying technologies

Noteworthy technologies in quantum computing include the following:

— *Quantum computing.* Quantum processors use the principles of quantum mechanics to perform simulations and process information. They can provide exponential performance improvements over classical computers for some applications.

— *Quantum communication.* This is the secure transfer of quantum information across space. It could ensure security of communications, enabled by quantum cryptography, even in the face of unlimited (quantum) computing power.

— *Quantum sensing.* Quantum sensors could provide measurements of various physical quantities at a sensitivity that is orders of magnitude higher than classical sensors.

'Moving away from pure R&D toward first applications, we see that companies are generating benefits and a new competitive edge from quantum computing by applying it in combination with classical computers for first simulations of ultracomplex systems.'

– Henning Soller, partner, Frankfurt

[41] "Bosch establishes startup for quantum sensing," Bosch press release, February 17, 2022.

Key uncertainties

The major uncertainties affecting quantum technologies include the following:

— *Technical challenges* include the ability to manage a sufficient quantity and quality of qubits over enough time to derive meaningful computational results.

— *Cost-effectiveness* may take time. Most calculations businesses require can be performed reasonably well by traditional supercomputers and at a much lower cost; this is expected to change once quantum advantage is achieved and general-purpose quantum computers take center stage.

— *An uncertain road* lies ahead. Current advancements in quantum technologies paint a promising future, but there may be potential barriers to adoption (for example, regulatory, technological, and financial) that are not yet apparent.

— *Ecosystems* are nascent. Only a handful of proven hardware platforms are commercially available at a small scale, and talent skilled in quantum computing is exceedingly rare; this may change as the technology matures and adoption increases.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with quantum technologies:

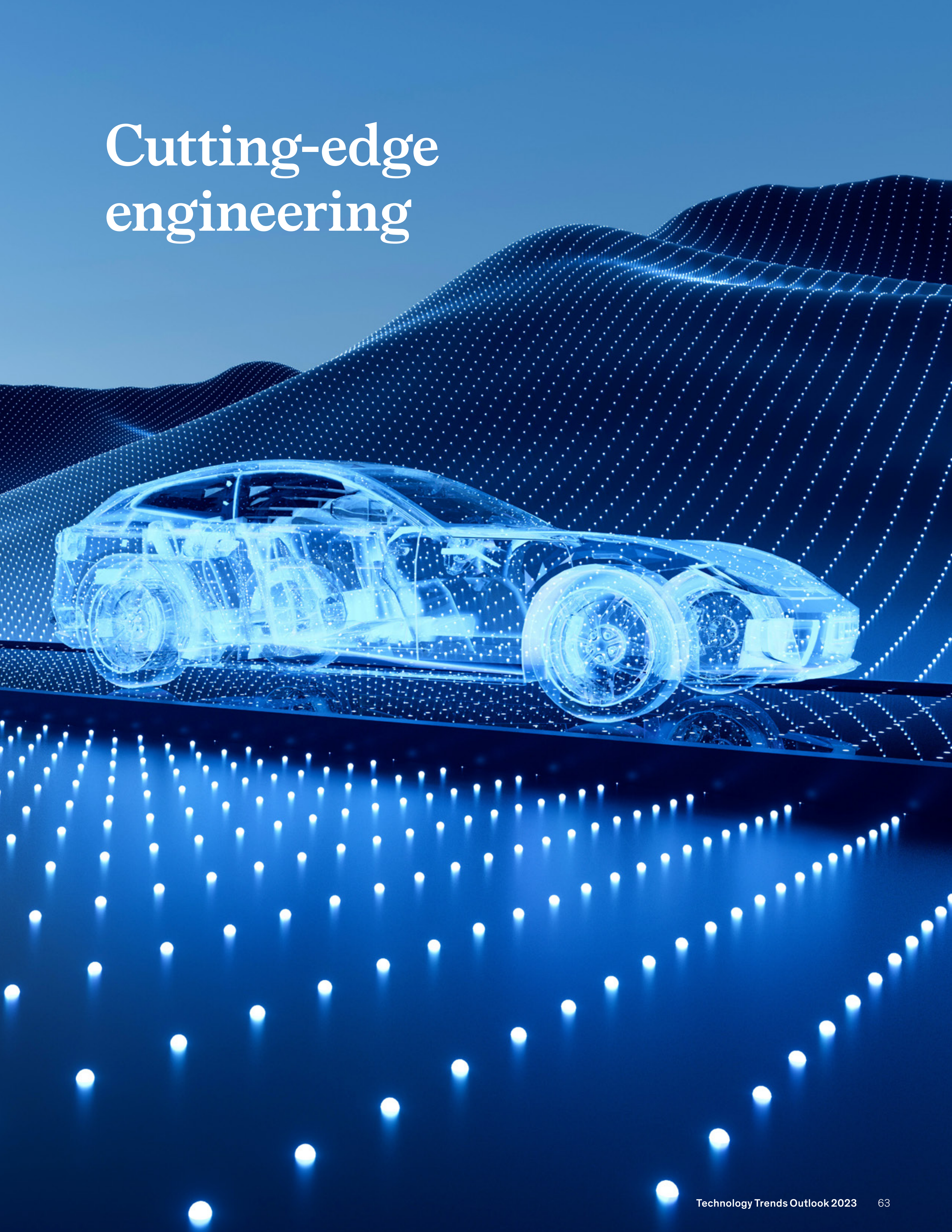
— Will quantum technology be ready in the next ten years?

— Will quantum technology reach its full disruptive potential?

— How should companies prepare for quantum technology?

— Will talent supply catch up to demand? What levers are available, and how can organizations help fill the talent gap?

Cutting-edge engineering



Future of mobility

The trend—and why it matters

More than a century after mass production of automobiles began, mobility has arrived at a second great inflection point: a shift toward autonomous driving, connectivity, the electrification of vehicles, and shared-mobility (ACES) technologies.[42] This shift promises to disrupt markets while improving efficiency and sustainability of land and air transportation of people and goods.[43] ACES technologies have seen increased adoption during the past decade, and the pace is accelerating as sustainability measures tighten, consumer preferences evolve, and innovation advances. For instance, autonomous-driving technologies are projected to create up to $400 billion in revenue by 2035.[44] Challenges remain in the near term, however, as innovators grapple with technological, regulatory, and supply chain issues that have, for example, delayed certain vehicle launches by up to six months.

Future of mobility

Scoring the trend

Interest, investment, and innovation measures for ACES technologies have approximately doubled over the past four years—with even higher growth in talent demand—pointing toward advances in new solutions and wider applications of existing ones.

Adoption rate score, 2022

0 1 **2** 3 4 5

None — Mainstream

Equity investment, 2022, $ billion

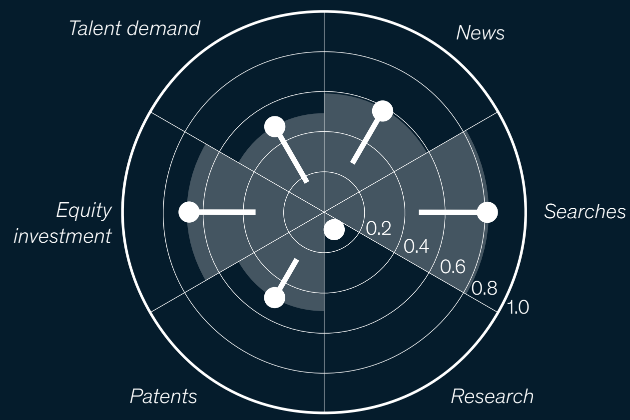
194

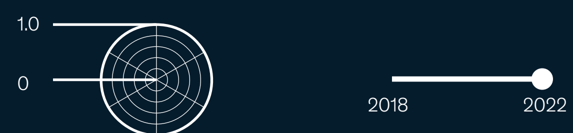
Job postings, 2021–22, % difference

+15

Industries affected: *Automotive and assembly; Aviation, travel, and logistics; Electric power, natural gas, and utilities; Financial services; Oil and gas; Public and social sectors; Retail*

Score by vector (0 = lower; 1 = higher)





Talent demand Ratio of actual skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

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42 "The trends transforming mobility's future," *McKinsey Quarterly*, March 8, 2019.
43 Kersten Heineke, Nicholas Laverty, Timo Möller, and Felix Ziegler, "The future of mobility," *McKinsey Quarterly*, April 19, 2023.
44 *Autonomous driving's future: Convenient and connected*, McKinsey, January 6, 2023.

Latest developments

These are some recent developments involving the future of mobility:

- *Leading players race to get ahead.* Robotaxi and roboshuttle players announced efforts to scale up their businesses in 2022, with strategic transactions being made to "acquihire" talent. Meanwhile, market size estimates for the micromobility and minimobility[45] industries advanced to $440 billion and $100 billion by 2030, respectively. Meanwhile, the global automotive software market is also expected to grow rapidly at a 5.5 percent CAGR from 2019 to 2030. Urban and advanced air mobility is similarly pushing forward, with leading electric vertical takeoff and landing (eVTOL) players aggressively pursuing important certifications by the mid-2020s.
- *Automotive suppliers contend with ongoing margin pressure.* In 2022, the margin pressures for automotive suppliers accelerated. Nearly all suppliers were affected by utility, gas, and electricity cost inflation and shortages, with 50 percent of suppliers seeing significant impacts. Semiconductor shortages, supply base consolidation, increasing costs for raw materials and freight, and the sometimes-daily volatility of automotive production volumes were also concerns.

'Autonomous vehicles will make our lives safer and more convenient. They'll also help us save money either via roboshuttles transporting us from A to B more cheaply and conveniently than private cars or via goods getting cheaper due to autonomous trucks.'

– Kersten Heineke, partner, Frankfurt

[45] Micromobility: primarily electric bicycles, mopeds, and e-kickscooters; minimobility: three- and four-wheeled electric vehicles that can fit one or two people.

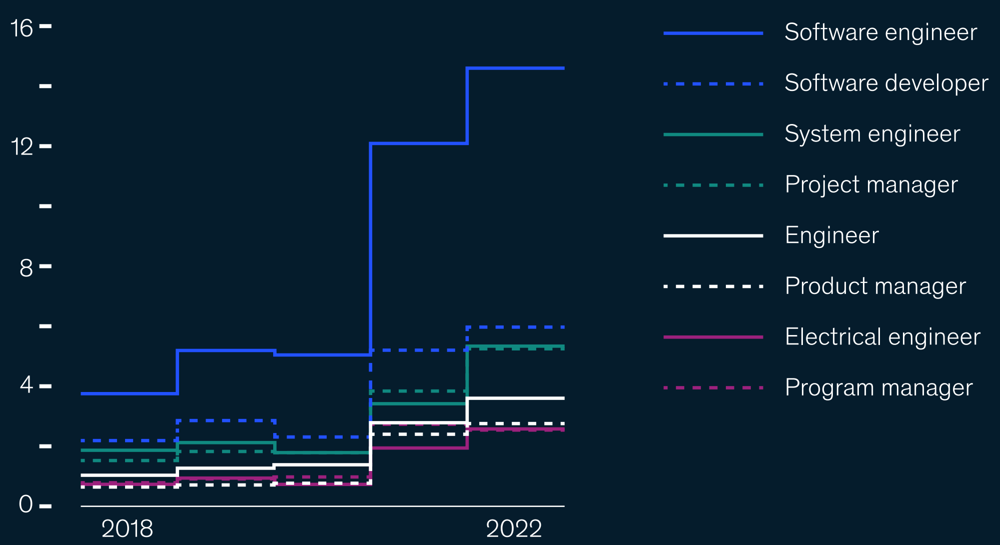
Talent market

Future of mobility

Demand

Job postings doubled between 2020 and 2021, with moderate but significant continued growth from 2021 to 2022. Given the pace of growth in the global automotive-software market, teams are likely to require significant numbers of software engineers and developers working alongside traditional engineers.

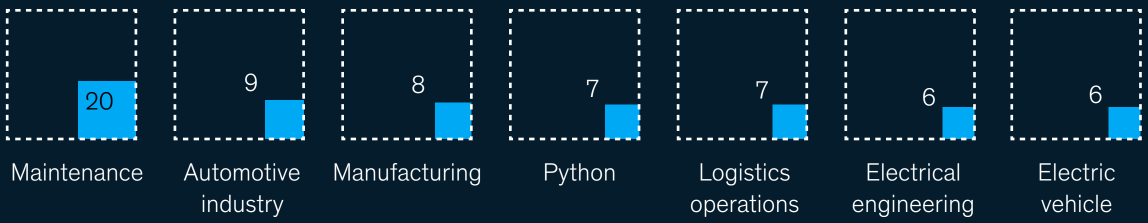
Job postings by title, 2018–22, thousands



Skills availability

The industry faces shortages of talent with key software and electrical skills.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand

In real life

Real-world examples involving the future of mobility include the following:

— Cruise, Waymo, and Amazon subsidiary Zoox began deploying autonomous mobility as a service by transporting passengers on a public road using an autonomous, purpose-built robotaxi.

— Einride has expanded into Germany, Europe's largest transportation market, with plans to offer digital, electric, and autonomous shipping using its Einride Pods and Einride Saga, an AI-powered freight mobility platform.

— Lime became the first global shared micromobility provider to achieve a full profitable year, announcing an adjusted EBITDA of $15 million for 2022 against a record $466 million in annual revenue—a 33 percent increase over 2021 bookings.

— Zipline, a next-generation logistics platform enabled by a fleet of autonomous, electric drones, estimates it can complete deliveries seven times faster than traditional automobiles and with 97 percent fewer emissions.

— In 2022, Archer Aviation unveiled its production-grade aircraft called Midnight, which is described as a safe, sustainable, and quiet four-passenger eVTOL aircraft on track for Federal Aviation Administration certification in 2024.

'The accelerated transition to clean transportation demands an unprecedented cross-sector effort involving, for example, vehicle manufacturers, suppliers, energy storage, recycling, and infrastructure.'

– Andreas Breiter, partner, Bay Area

Underlying technologies

A future of efficient, sustainable mobility, we believe, will be defined by ACES and adjacent technologies, such as the following:

— *Autonomous technologies.* Automated systems with sensors and AI can make independent decisions based on data they collect.

— *Connected-vehicle technologies.* Equipment, applications, and systems use vehicle-to-everything communications to improve safety and efficiency.

— *Electrification technologies.* These solutions replace vehicle components that operate on a conventional energy source with those that operate on electricity.

— *Shared-mobility solutions.* Hardware and advanced digital solutions, as well as new business models and social adoption, enable the use of alternative shared modes of transportation in addition to—or instead of—privately owned vehicles.

— *Materials innovation.* The use of new materials (for example, carbon fiber and other lightweight materials) and processes (such as engine downsizing) can improve efficiency and sustainability.

— *Value chain decarbonization.* In addition to electrification, technical levers (such as green primary materials) can abate emissions from materials' production and can increase the use of recycled materials.

Key uncertainties

The major uncertainties affecting the future of mobility include the following:

— *The global energy supply expansion* that is required to meet electric-vehicle (EV) demand remains uncertain. Demand for lithium-ion batteries is surging as EV production expands, necessitating more and larger battery factories. While announcements about future battery supply currently match expected demand, McKinsey research projects that a significant portion of announced future supply will not materialize, so shortages are likely to occur.[46] At the same time, critical upgrades are required to the EV-charging infrastructure: Europe, for instance, may need to invest upward of €240 billion to complete extensive utility grid updates, increase renewable-energy production capacity, and provide the estimated 3.4 million public charging points required by 2030 (up from 375,000 in 2021).

— *Safety and accountability concerns* surround uncrewed and autonomous-mobility technologies.

— *Technology uncertainties* about batteries with sufficient range to support more applications (such as air mobility) may hinder greater adoption.

— *Customer perceptions* of noise and visual impact (for example, noise pollution from delivery drones) remain in play.

— *Equipment and infrastructure costs* are factors for new modes of transportation (for instance, building EV charging networks).

— *Regulation shifts* will accompany the development of mainstream certification frameworks (for example, controlling expanded air traffic).

— *Privacy and security concerns* for underlying AI algorithms and workflows that rely on consumer data should be addressed.

— *Access to sufficient resources* (such as raw materials for battery production and software developers for autonomous-driving software) will be required to scale these technologies.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with ACES technologies:

— What share of vehicle sales will autonomous vehicles account for?

— How will the future of mobility trends shape cities?

— What needs to be in place for advancements in shared mobility to deliver on anticipated financial and environmental impact?

— What regulatory barriers should innovators overcome to enable widespread adoption?

— What scale will advanced air mobility achieve in the next decade?

— When should customers expect affordable advanced-air-mobility solutions?

[46] Kersten Heineke and Timo Möller, "Future mobility 2022: Hype transitions into reality," McKinsey, March 10, 2023.

Future of bioengineering

The trend—and why it matters

Breakthroughs in biology, combined with innovations in digital technology, could help organizations respond to demands in areas as diverse as healthcare, food and agriculture, consumer products, sustainability, and energy and materials production by creating new products and services. McKinsey research suggests that 400 use cases for bioengineering, almost all of which are scientifically feasible today, could have an economic impact of $2 trillion to $4 trillion per year from 2030 to 2040. While certain gene therapies and bioproducts have gained acceptance, ethical, regulatory, and public-perception issues will need to be settled for bioengineering to realize its full economic potential.

Future of bioengineering

Scoring the trend

Bioengineering ranked second among the trends for publications and research in 2022. News coverage has almost doubled since 2018, while talent demand has nearly tripled in the same time frame, signaling excitement about the trend's potential.

Adoption rate score, 2022

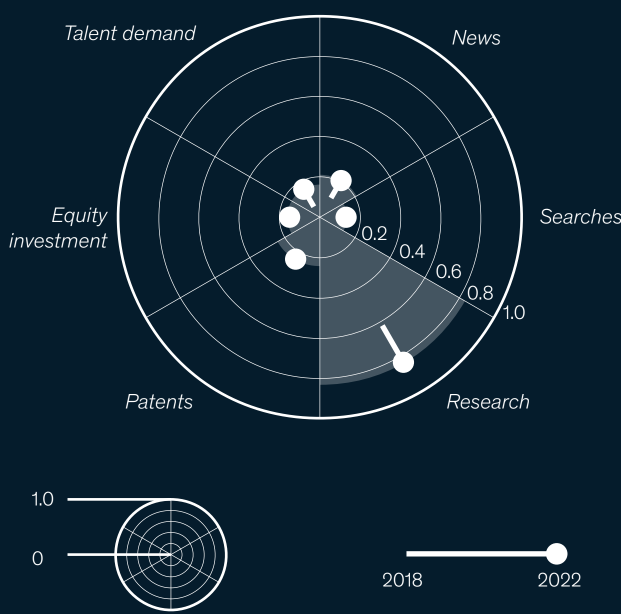
0 1 2 **3** 4 5

None — Mainstream

Equity investment, 2022, $ billion	**Job postings, 2021–22,** % difference
43	–19

Industries affected: *Agriculture; Chemicals; Consumer packaged goods; Healthcare systems and services. Pharmaceuticals and medical products*

Score by vector (0 = lower; 1 = higher)



Talent demand Ratio of actual skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

These are some recent developments involving the future of bioengineering:

- *Successes in omics-based therapies pave the way for further advances.* The recent successes of mRNA-based COVID-19 vaccines sparked an uptick in research activity around RNA-based therapeutics—more than 50 currently fill the clinical pipeline worldwide.[47] Additionally, the US Food and Drug Administration (FDA) approved five new viral-vector gene and related therapies in 2022, including Ferring Pharmaceuticals' Adstiladrin for bladder cancer and CSL's Hemgenix to treat hemophilia B. As viral-vector therapies shift beyond ultrarare indications and mRNA technology becomes commonplace, greater focus will go toward the tunability of mRNA and gene therapies to develop personalized "n = 1" drugs. Investments in manufacturing facilities to obtain higher yields, achieve lower cost of goods sold, and produce these personalized medicines will enable innovators to better capture the increasing demand for novel therapeutics.
- *Cultivated meat approaches increased commercial availability, but obstacles remain.* Since diners first feasted upon a cultivated meat product at a Singapore-based restaurant in December 2020, the technology has continued to advance: innovators have reduced the cost of production by 99 percent versus early prototypes, and the FDA completed its first premarket safety review of the technology in November 2022. Present estimates suggest that cultivated meat could provide 0.5 percent of the world's meat supply by 2030, representing billions of pounds of meat and up to $25 billion in revenue.
- *Climate commitments accelerate demand for biomaterials.* Increasing focus on sustainability (including material reduction, sourcing, and end-of-life fate) has changed the basis of competition in the chemicals and materials market, creating new demand for biomaterials that meet the desired profile. New targets released in 2023 from the US government require that at least 30 percent of US chemical demand in 20 years be met via sustainable and cost-effective biomanufacturing pathways.

'Bioengineering stands to benefit immensely from three simultaneous trends. First, the cost of data collection is rapidly coming down, with DNA sequencing as a prime example. Second, the ability to analyze and derive insights from data is accelerating, with generative AI being the most visible recent example. Third, the cost of running experiments is going down as evidenced by, for example, DNA synthesis costs.'

– Tom Brennan, partner, Philadelphia

[47] Qiongyu Duan et al., "How far are the new wave of mRNA drugs from us? mRNA product current perspective and future development," *Frontiers in Immunology*, September 12, 2022, Volume 13.

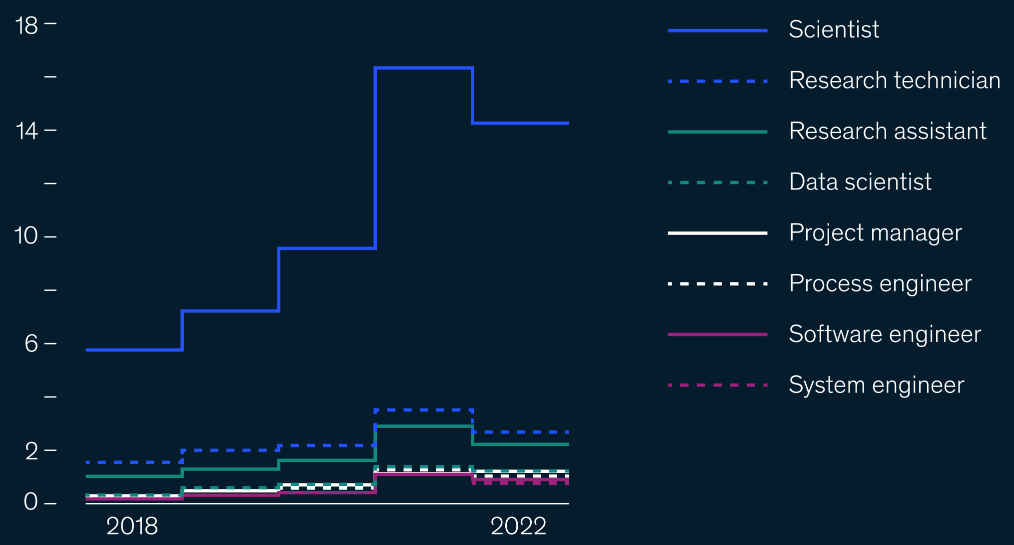
Talent market

Future of bioengineering

Demand

Bioengineering and medical technologies often require years—or decades—of research before going to market. This creates a field with long hiring cycles and high demand for scientific and research talent. Job postings in the field have more than doubled since 2018, with a spike during the COVID-19 pandemic that moderated in 2022 as biotech funding decreased. The future of bioengineering has higher demand for scientists and researchers than other tech trends.

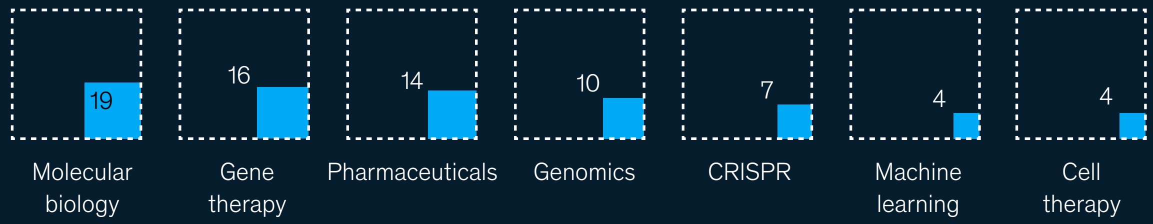
Job postings by title, 2018–22, thousands



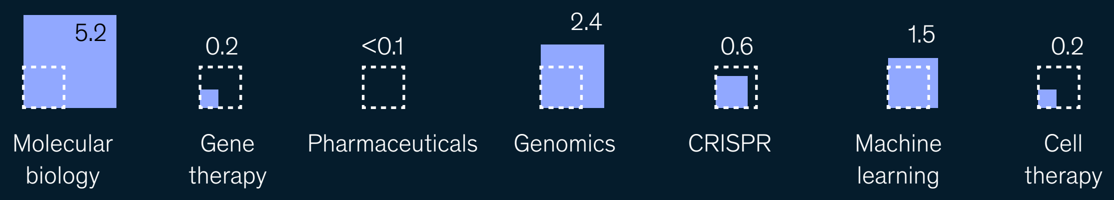
Skills availability

While the supply of talent in molecular biology is high relative to demand, the supply of talent for newer technical skills—such as gene therapy, cell therapy, and molecular cloning—is low.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



In real life

Real-world examples involving the future of bioengineering include the following:

- Moderna now has 48 mRNA-based development programs in its pipeline, including one focused on new iterations of its novel COVID-19 vaccine,[48] a rare-disease program addressing propionic acidemia in Phase II, and a personalized cancer vaccine program in collaboration with Merck, also in Phase II.
- Bluebird Bio announced in August 2022 that the FDA approved its one-time gene therapy that treats the underlying genetic cause of beta thalassemia, a blood disorder that would otherwise require red-blood-cell transfusions.
- Upside Foods, a San Francisco-based cultivated meat start-up, announced in November 2022 that the FDA deemed its chicken cultured from animal cells to be safe for human consumption, marking the agency's first-ever review of a cultivated meat product.
- Korea-based LG Chem and ADM launched a joint venture in August 2022 for US-based production of lactic acid and polylactic acid to meet growing demand for a variety of plant-based products, including bioplastics.

Underlying technologies

The future of bioengineering will be defined by advancements in omics, tissue engineering, and biomaterials.

- *Omics.* Biological sciences ending in the suffix "-omics," such as genomics and proteomics, focus on a different class of molecule and its functions. Omics are central to the development of bioengineering applications such as viral-vector gene therapy (which uses modified viruses to permanently replace poorly functioning genes that cause genetic diseases) and mRNA therapy (which uses messenger RNA to trigger the synthesis of proteins that can help prevent or fight disease).
- *Tissue engineering.* This technology enables the modification of cells, tissues, and organs. Cultivated meat is one example of a product based on tissue-engineering methods; it is made by taking a sample of animal cells and growing it in a controlled environment to produce tissue that is similar to meat from whole animals.
- *Biomaterials.* Materials made using bioengineering technology are known as biomaterials. They fall into several different categories: bio-based drop-in chemicals (which can replace chemicals traditionally made from petrochemicals without changing surrounding operations), bioreplacements (new materials made from bio-based chemicals that provide similar quality and cost but better environmental performance than traditional chemicals), and bio-better materials (completely new materials produced via biochemical synthesis).

'The bioengineering world continues to see breakthroughs, and its economics and impact look promising. COVID-19 provided a spike in validation in some areas, such as RNA therapy and other omics, though others, like synthetic biology, have seen fresh questions about potential applications.'

– Erika Stanzl, partner, Zurich

[48] "Research: mRNA pipeline," Moderna.

Key uncertainties

The major uncertainties affecting the future of bioengineering include the following:

— *Public perceptions* of the safety, cost, and quality of bioengineered products could determine how quickly markets develop.

— *Regulation of bioengineering technology and products* will play a part in governing the pace of advancements.

— *Ethical concerns* surround the possibilities for modifying living organisms.

— *Unintended consequences* could occur, as biological systems are self-replicating, self-sustaining, and highly interconnected. Changes to one part of a system can have negative cascading effects across an entire ecosystem or species.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with bioengineering technologies:

— How will society consider diverse values and principles and determine an appropriate extent for genome editing?

— In conjunction with business adoption, how will mainstream audiences perceive and adopt bioengineering? For example, how does cultivated meat fit within existing diets?

— As cross-disciplinary innovations make new applications possible, what will be the long-term impact and near-term implications of bioengineering?

Future of space technologies

The trend—and why it matters

The most significant development for the space industry in the past five to ten years has been decreasing technology costs, which are making new capabilities and applications more accessible. Lower component costs have been propelled strongly by reductions in the size, weight, power, and cost of satellites and launch vehicles. These reductions have led to changes in system architectures, such as the shift from individual, large geosynchronous-equatorial-orbit (GEO) satellites to smaller, distributed low-Earth-orbit (LEO) satellites, as well as the increasing interest in space technologies from traditional nonspace companies. The use of space technologies and remote-sensing analytics is substantial today, and analysis suggests that the space market could exceed $1 trillion by 2030.[49] The future space economy could encompass activities that currently aren't being pursued at scale, such as in-orbit manufacturing, power generation, and space mining, as well as scalable human spaceflight.

Future of space technologies

Scoring the trend

Scores for space technology momentum remain subdued but have exhibited steady growth over all dimensions since 2018.

Adoption rate score, 2022

0 1 2 3 4 5

None Mainstream

Equity investment, 2022, $ billion

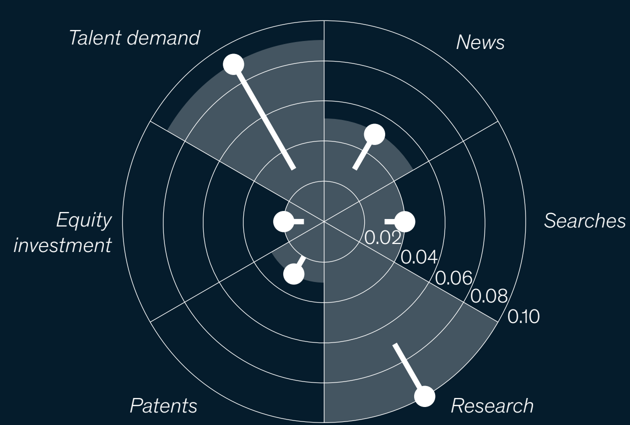
8

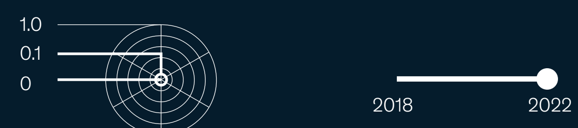
Job postings, 2021–22, % difference

+16

Industries affected: *Aerospace and defense; Telecommunications*

Score by vector (0 = lower; 1 = higher)





Talent demand Ratio of actual skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

[49] Michael Sheetz, "Bank of America expects the space industry to triple to a $1.4 trillion market within a decade," CNBC, October 2, 2020.

Latest developments

These are some recent developments involving space technologies:

- *Private sector leads resurgence of lunar activity.* Japanese company ispace, which went public in April 2023, and Astrobotic Technology, in the United States, are just a couple of the private companies racing to launch lunar landers. While ispace's December 2022 launch was unsuccessful, the company already has another lander launch planned for 2024. Astrobotic recently delayed a planned May 2023 launch. The company that finally lands a vehicle successfully will become the first to put a private spacecraft on the moon.
- *A watershed year for launch vehicles is on the horizon.* Several new highly anticipated launch vehicles are expected to debut in 2023 and 2024, including the SpaceX's superheavy *Starship*, designed to carry larger loads; the *Vulcan Centaur*, from United Launch Alliance, which is designed to carry satellites into orbit; and Blue Origin's *New Glenn*, which will carry a portion of Amazon's Project Kuiper satellites. These vehicles will help address the expected growth in demand for launch capacity.
- *Increased interest in space comes from other sectors.* Space is increasingly being considered for applications in areas outside the space industry. Hitachi Energy has developed satellite vegetation management for utilities companies to better manage and respond to the impact of storms on surrounding vegetation (for example, a wildfire ignited from electrical lines during a storm).[50] Several insurance carriers are also exploring the use of satellite data to predict claims after disasters, and financial companies are using similar data to make predictions about commodities.
- *Direct-to-device satellite coverage sees investment.* In 2022, Apple added emergency satellite coverage to its iPhone 14 through a partnership with Globalstar. The emergency SOS integration has already made the news for its use in successful rescues. Other companies, including Amazon and T-Mobile, have made plans to offer satellite coverage that can be used in an emergency or to reach areas of the world that are not covered by usual service.

'Space already plays a large role in our lives, though somewhat behind the scenes. We are entering a new age. Space is moving into the public eye, with the potential to positively influence every individual on the planet and even the planet itself. We are at the beginning of the golden age of space for humanity.'

– Ryan Brukardt, senior partner, Miami

[50] "Vegetation manager for rail: Limit downtime by managing vegetation around tracks," Hitachi Energy.

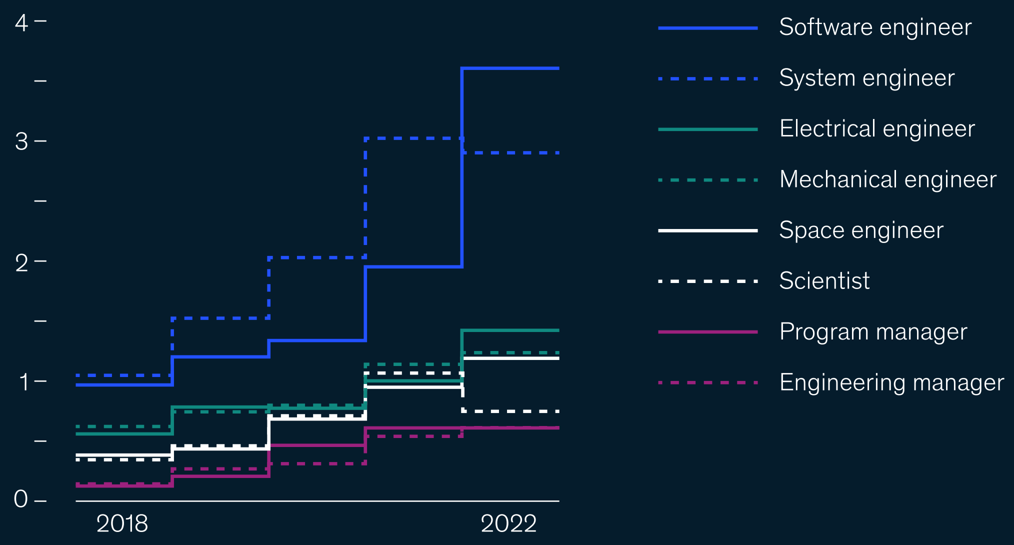
Talent market

Future of space technologies

Demand

The space technology labor market has had a ten-year run of growth during which job postings in the industry have more than doubled. Job postings grew significantly in 2021, during the peak year for private capital into space, and have continued to increase in 2022. Although space technologies rely heavily on traditional engineering fields, such as systems, electrical, and mechanical engineering, companies are hiring increasingly large numbers of software engineers. Prior McKinsey research indicates that traditional aerospace and defense companies may need to offer more flexibility and new career paths to attract top talent for these roles.[1]

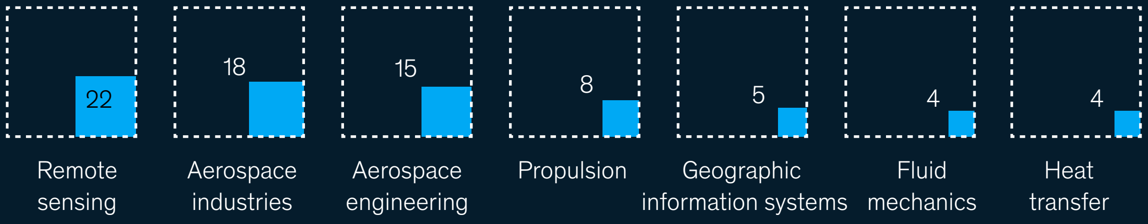
Job postings by title, 2018–22, thousands



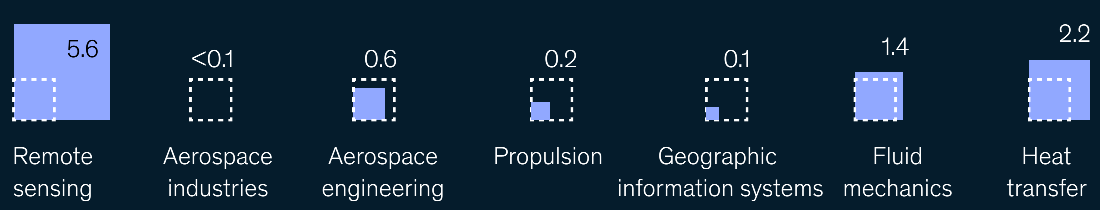
Skills availability

Many roles require knowledge of remote sensing and specialized engineering skills.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



[1] Varun Marya, Michael Park, Andy Voelker, and Brooke Weddle, “Navigating the gray-to-green transition in aerospace and defense,” McKinsey, March 16, 2023.

In real life

Real-world examples involving the use of space technologies include the following:

- Starlink has partnered with several school districts in rural areas of the United States to provide high-speed internet service to schools and students in underserved areas. Pilot programs are ongoing in Arizona, New Mexico, North Carolina, Ohio, South Carolina, Texas, and Virginia and are being funded by a combination of donations and government subsidies.
- The Common Market for Eastern and Southern Africa (COMESA) and the Alliance for a Green Revolution in Africa (AGRA) co-led the development of a digital regional food balance sheet powered by satellite data to provide the common data and analytical infrastructure required to predict near real-time food production and stock levels. The food balance sheet led to increased efficiency in government food reserve purchases.
- Rio Tinto, a leading global producer of iron ore, announced a partnership with Pixxel in early 2022. Using Pixxel's hyperspectral satellite imaging, a form of high-resolution imaging that analyzes a wide spectrum of light, Rio Tinto plans to identify mineral resources and monitor both active and closed mining sites.
- Amazon's Project Kuiper is aiming to provide consumer broadband service globally through an LEO satellite network. It is developing compact, varying-capacity customer terminals, with some offering speeds up to one gigabyte per second. The project anticipates the commencement of mass satellite production in late 2023, and the first launch is expected in 2024.

Underlying technologies

The foundational technologies include the following:

- *Small satellites.* Modular small satellites can be custom built—by using CubeSat architectures and standard-size building blocks—to perform a widening variety of missions.
- *Remote sensing.* Full-spectrum imaging and monitoring are used for observing Earth's features such as oceanography, weather, and geology.
- *SWaP-C advancements.* Reductions in the size, weight, power, and cost (SWaP-C) of satellites and launch vehicles have increased the cost-effectiveness of space technology and associated use cases.
- *Launch technology advancements.* Technology advancements (for example, computer-aided design, material sciences, and so on), the reuse of booster structures and engines, and increases in launch rates are opening up access to space.
- *Promising new technologies.* Technologies including laser communications, nuclear propulsion, electronically scanned antennas, and automated satellite operations, are on the horizon.

'This is the most dynamic time so far in the history of human space activities. Not every idea will succeed, but the entrepreneurship and commercial potential are unprecedented.'

– Chris Daehnick, associate partner, Denver

Key uncertainties

The major uncertainties affecting the future of space technologies include the following:

— *Cost-effectiveness* of space technologies is required to enable further scalability.

— *Governance* mechanisms need to better define allocation of spectrum and orbit usage rights to accommodate the increasing number of players, satellites, and applications.

— *Cyber risks,* including data breaches, malware, and other cyberattacks, are growing in number and complexity because of the proliferation of commercial players.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with space technologies:

— Can the existing spectrum allocation system survive in an increasingly competitive and polarized world?

— What will it take to avoid a tragedy of the commons in orbital-debris management?

— How can leaders define ownership and access rights?

— How can leaders effectively manage space debris and traffic?

A sustainable world

Electrification and renewables

Electrification and renewables help drive toward net-zero commitments and include solar-, wind-, and hydro-powered renewables and other renewables; nuclear energy; hydrogen; sustainable fuels; and electric-vehicle charging.

Industries affected: *Agriculture; Automotive and assembly; Aviation, travel, and logistics; Chemicals; Construction and building materials; Electric power, natural gas, and utilities; Metals and mining; Oil and gas; Real estate*

Link: Global Energy Perspective 2022 report

Adoption rate score, 2022

0 1 **2** 3 4 5

None — Mainstream

Equity investment, 2022,[1]
$ billion

288

Job postings, 2021–22,
% difference

+27

[1]Capital expenditure–related investments for 2022 totaled $578 billion, as noted in the *2022 Global Energy Perspective* report.

Climate technologies beyond electrification and renewables

Climate technologies include carbon capture, utilization, and storage (CCUS); carbon removals; natural climate solutions; circular technologies; alternative proteins and agriculture; water and biodiversity solutions and adaptation; and technologies to track net-zero progress.

Industries affected: *Agriculture; Automotive and assembly; Aviation, travel, and logistics; Chemicals; Construction and building materials; Electric power, natural gas, and utilities; Metals and mining; Oil and gas; Real estate*

Link: McKinsey Platform for Climate Technologies

Adoption rate score, 2022

0 1 **2** 3 4 5

None — Mainstream

Equity investment, 2022,[1]
$ billion

86

Job postings, 2021–22,
% difference

+8

[1]Capital expenditure–related investments for 2022 totaled $98 billion, as noted in the *2022 Global Energy Perspective* report.

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