Science and technology | Red moon risen

China has become a scientific superpower

From plant biology to superconductor physics the country is at the cutting edge

PHOTOGRAPH: LIU XU/POLARIS/EYEVINE

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IN THE ATRIUM of a research building at the Chinese Academy of Sciences (CAS) in Beijing is a wall of patents. Around five metres wide and two storeys high, the wall displays 192 certificates, positioned in neat rows and tastefully lit from behind. At ground level, behind a velvet rope, an array of glass jars contain the innovations that the patents protect: seeds.

CAS—the world's largest research organisation—and institutions around China produce a huge amount of research into the biology of food crops. In the past few years Chinese scientists have discovered a gene that, when removed, boosts the length and weight of wheat grains, another that improves the ability of crops like sorghum and millet to grow in salty soils and one that can increase the yield of maize by around 10%. In autumn last year, farmers in Guizhou completed the second harvest of genetically modified giant rice that was developed by scientists at CAS.

The Chinese Communist Party (CCP) has made agricultural research—which it sees as key to ensuring the country's food security—a priority for scientists. Over the past decade the quality and the quantity of crop research that China produces has grown immensely, and now the country is widely regarded as a leader in the field. According to an editor of a prestigious European plant-sciences journal, there are some months when half of the submissions can come from China.

A journey of a thousand miles

The rise of plant-science research is not unique in China. In 2019 *The Economist* surveyed the research landscape in the country and asked whether China could one day become a scientific superpower. Today, that question has been unequivocally answered: "yes". Chinese scientists recently gained the edge in two closely watched measures of high-quality science, and the country's growth in top-notch research shows no sign of slowing. The old

science world order, dominated by America, Europe and Japan, is coming to an end.

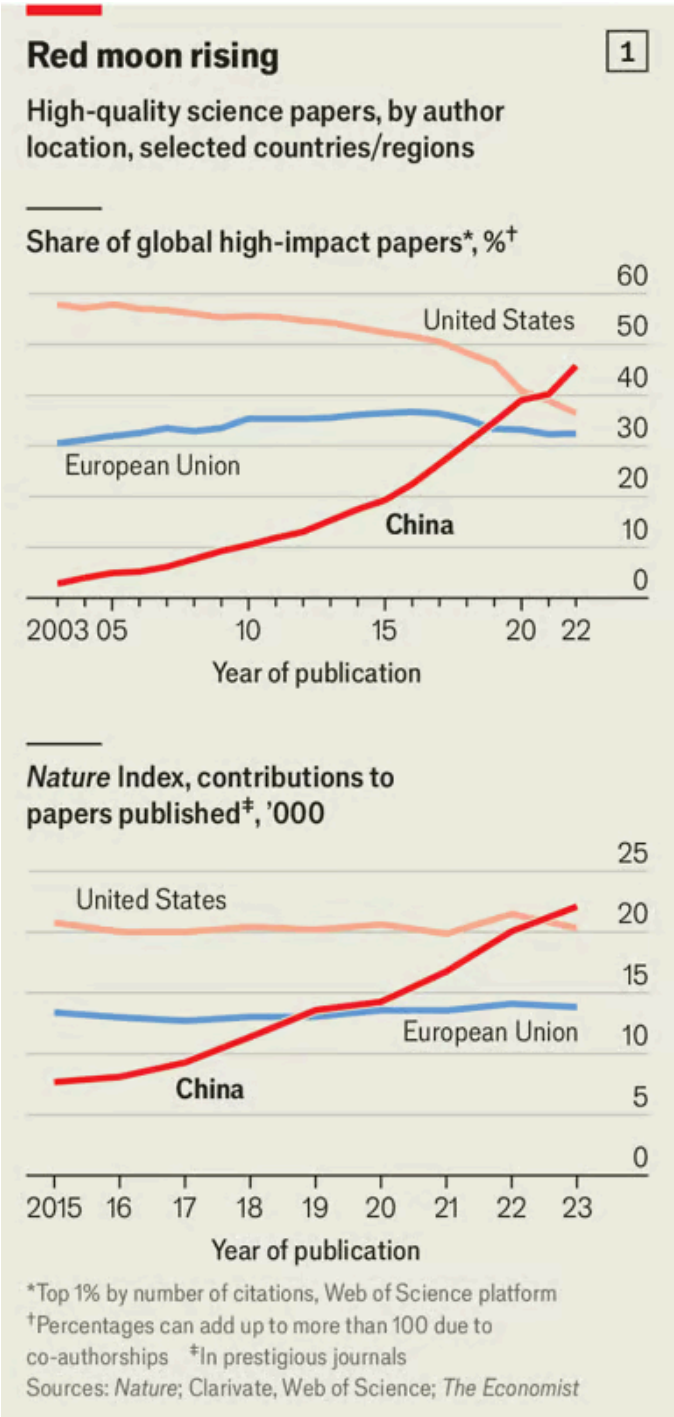


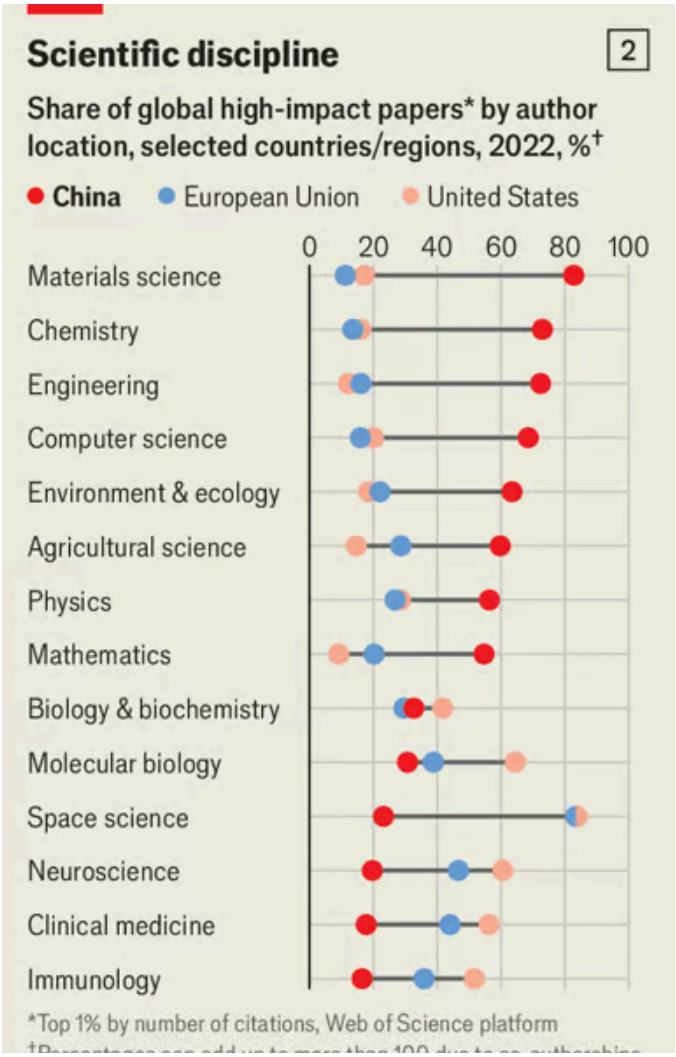
CHART: THE ECONOMIST

One way to measure the quality of a country's scientific research is to tally the number of high-impact papers produced each year—that is, publications that are cited most often by other scientists in their own, later work. In 2003 America produced 20 times more of these high-impact papers than China, according to data from Clarivate, a science analytics company (see chart 1). By 2013 America produced about four times the number of top papers and, in the most recent release of data, which examines papers from 2022, China had surpassed both America and the entire European Union (EU).

Metrics based on citations can be gamed, of course. Scientists can, and do, find ways to boost the number of times their paper is mentioned in other studies, and a recent working paper, by Qui Shumin, Claudia Steinwender and Pierre Azoulay, three economists, argues that Chinese researchers cite their compatriots far more than Western researchers do theirs. But China now leads the world on other benchmarks that are less prone to being gamed. It tops the *Nature* Index, created by the publisher of the same name, which counts the contributions to articles that appear in a set of prestigious journals. To be selected for publication, papers must be approved by a panel of peer reviewers who assess the study's quality, novelty and potential for impact. When the index was first launched, in 2014, China came second, but its

contribution to eligible papers was less than a third of America's. By 2023 China had reached the top spot.

According to the Leiden Ranking of the volume of scientific research output, there are now six Chinese universities or institutions in the world top ten, and seven according to the *Nature* Index. They may not be household names in the West yet, but get used to hearing about Shanghai Jiao Tong, Zhejiang and Peking (Beida) Universities in the same breath as Cambridge, Harvard and ETH Zurich. "Tsinghua is now the number one science and technology university in the world," says Simon Marginson, a professor of higher education at Oxford University. "That's amazing. They've done that in a generation."



Today China leads the world in the physical sciences, chemistry and Earth and environmental sciences, according to both the *Nature* Index and citation measures (see chart 2). But America and Europe still have substantial leads in both general biology and medical sciences. "Engineering is the ultimate Chinese discipline in the modern period," says Professor Marginson, "I think that's partly about military technology and partly because that's what you need to develop a nation."

Applied research is a Chinese strength. The country dominates publications on perovskite solar panels, for example, which offer the possibility of being far more

Percentages can add up to more than 100 due to co-authorships
Sources: Clarivate, Web of Science; *The Economist*

CHART: THE ECONOMIST

possibility of being far more efficient than conventional silicon cells at converting sunlight into electricity. Chinese chemists have developed a new way to extract hydrogen from seawater using a specialised membrane to separate out pure water, which can then be split by electrolysis. In May 2023 it was announced that the scientists, in collaboration with a state-owned Chinese energy company, had developed a pilot floating hydrogen farm off the country's south-eastern coast.

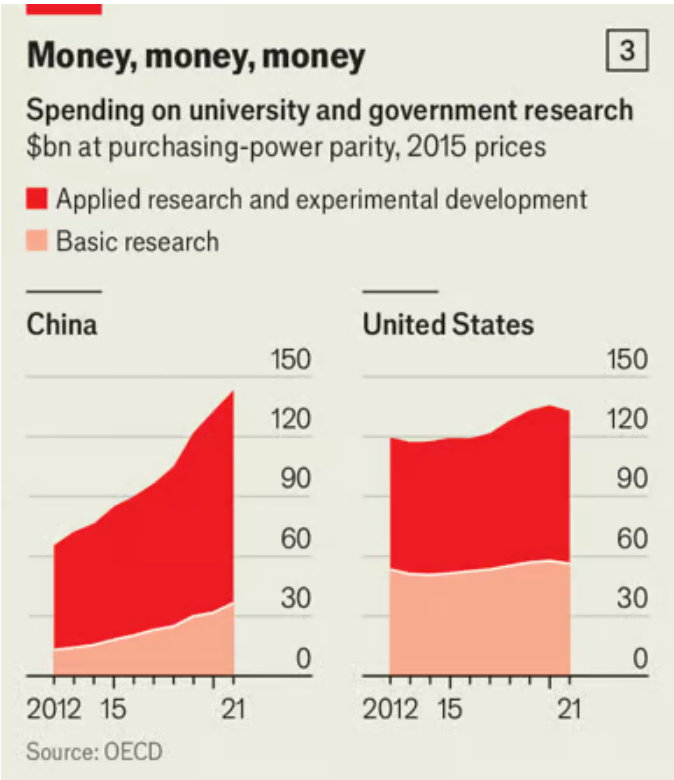
China also now produces more patents than any other country, although many are for incremental tweaks to designs, as opposed to truly original inventions. New developments tend to spread and be adopted more slowly in China than in the West. But its strong industrial base, combined with cheap energy, means that it can quickly spin up large-scale production of physical innovations like materials. "That's where China really has an advantage on Western countries," says Jonathan Bean, CEO of Materials Nexus, a British firm that uses AI to discover new materials.

The country is also signalling its scientific prowess in more conspicuous ways. Earlier this month, China's *Chang'e-6* robotic spacecraft touched down in a gigantic crater on the far side of the Moon, scooped up some samples of rock, planted a Chinese flag and set off back towards Earth. If it successfully returns to Earth at the end of the month, it will be the first mission to bring back samples from this hard-to-reach side of the Moon.

First, sharpen your tools

The reshaping of Chinese science has been achieved by focusing on three areas: money, equipment and people. In real terms, China's spending on research and development (R&D) has grown 16-fold since 2000. According to the most recent data from the OECD, from 2021, China still lagged behind America on overall R&D spending, dishing out $668bn, compared with $806bn

for America at purchasing-power parity. But in terms of spending by universities and government institutions only, China has nudged ahead. In these places America still spends around 50% more on basic research, accounting for costs, but China is splashing the cash on applied research and experimental development (see chart 3).



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Money is meticulously directed into strategic areas. In 2006 the CCP published its vision for how science should develop over the next 15 years. Blueprints for science have since been included in the CCP's five-year development plans. The current plan, published in 2021, aims to boost research in quantum technologies, AI, semiconductors, neuroscience, genetics and biotechnology, regenerative medicine, and exploration of "frontier areas" like deep space, deep oceans and Earth's poles.

Creating world-class universities and government institutions has also been a part of China's scientific development plan. Initiatives like "Project 211", the "985 programme" and the "China Nine League" gave money to selected labs to develop their research capabilities. Universities paid staff bonuses—estimated at an average of $44,000 each, and up to a whopping $165,000—if they published in high-impact international journals.

Building the workforce has been a priority. Between 2000 and 2019, more than 6m Chinese students left the country to study abroad, according to China's education ministry. In recent years they have flooded back, bringing their newly acquired skills and knowledge with them. Data from the OECD suggest that, since the late 2000s, more scientists have been returning to the country than leaving. China now employs more researchers than both America and the entire EU.

Many of China's returning scientists, often referred to as "sea turtles" (a play on the Chinese homonym *haigui*, meaning "to return from abroad") have been drawn home by incentives. One such programme launched in 2010, the "Youth Thousand Talents", offered researchers under 40 one-off bonuses of up to 500,000 yuan (equivalent to roughly $150,000 at purchasing-power parity) and grants of up to 3m yuan to get labs up and running back home. And it worked. A study published in *Science* last year found that the scheme brought back high-calibre young researchers—they were, on average, in the most productive 15% of their peers (although the real superstar class tended to turn down offers). Within a few years, thanks to access to more resources and academic manpower, these returnees were lead scientists on 2.5 times more papers than equivalent researchers who had remained in America.

As well as pull, there has been a degree of push. Chinese scientists working abroad have been subject to increased suspicion in recent years. In 2018 America launched the China Initiative, a largely unsuccessful attempt to root out Chinese spies from industry and academia. There have also been reports of students being deported because of their association with China's "military-civilian fusion strategy". A recent survey of current and former Chinese students studying in America found that the share who had experienced racial abuse or discrimination was rising.

The availability of scientists in China means that, for example in quantum computing, some of the country's academic labs are more like commercial labs in the West, in terms of scale. "They have research teams of 20, 30, even 40 people working on the same experiments, and they make really good progress," says Christian Andersen, a quantum researcher at Delft University. In 2023 researchers working in China broke the record for the number of quantum bits, or qubits, entangled inside a quantum computer.

China has also splurged on scientific kit. In 2019, when *The Economist* last surveyed the state of the country's scientific research, it already had an enviable inventory of flashy hardware including supercomputers, the world's

enviable inventory of flashy hardware including supercomputers, the world's largest filled-aperture radio telescope and an underground dark-matter detector. The list has only grown since then. The country is now home to the world's most sensitive ultra-high-energy cosmic-ray detector (which has recently been used to test aspects of Albert Einstein's special theory of relativity), the world's strongest steady-state magnetic field (which can probe the properties of materials) and soon will have one of the world's most sensitive neutrino detectors (which will be used to work out which type of these fundamental subatomic particles has the highest mass). Europe and America have plenty of cool kit of their own, but China is rapidly adding hardware.

Individual labs in China's top institutions are also well equipped. Niko McCarty, a journalist and former researcher at the Massachusetts Institute of Technology who was recently given a tour of synthetic biology labs in China, was struck by how, in academic institutions, "the machines are just more impressive and more expansive" than in America. At the Advanced Biofoundry at the Shenzhen Institute of Advanced Technology, which the country hopes will be the centre of China's answer to Silicon Valley, Mr McCarty described an "amazing building with four floors of robots". As Chinese universities fill with state-of-the-art equipment and elite researchers, and salaries become increasingly competitive, Western institutions look less appealing to young and ambitious Chinese scientists. "Students in China don't think about America as some "scientific Mecca" in the same way their advisers might have done," said Mr McCarty.

All the flowers of all the tomorrows PHOTOGRAPH: ALAMY

Take AI, for example. In 2019 just 34% of Chinese students working in the field stayed in the country for graduate school or work. By 2022 that number was 58%, according to data from the AI talent tracker by MacroPolo, an American think-tank (in America the figure for 2022 was around 98%). China now contributes to around 40% of the world's research papers on AI, compared with around 10% for America and 15% for the EU and Britain combined. One of the most highly cited research papers of all time, demonstrating how deep neural networks could be trained on image recognition, was written by AI researchers working in China, albeit for Microsoft, an American company. "China's AI research is world-class," said Zachary Arnold, an AI analyst at the Georgetown Centre for Emerging Security and Technology. "In areas like computer vision and robotics, they have a significant lead in research publications."

Growth in the quality and quantity of Chinese science looks unlikely to stop anytime soon. Spending on science and technology research is still increasing —the government has announced a 10% increase in funding in 2024. And the country is training an enormous number of young scientists. In 2020 Chinese universities awarded 1.4m engineering degrees, seven times more than America did. China has now educated, at undergraduate level, 2.5 times more of the top-tier AI researchers than America has. And by 2025, Chinese universities are expected to produce nearly twice as many PhD graduates in science and technology as America.

To see further, ascend another floor

Although China is producing more top-tier work, it still produces a vast amount of lower-quality science too. On average, papers from China tend to have lower impact, as measured by citations, than those from America, Britain or the EU. And while the chosen few universities have advanced, mid-level universities have been left behind. China's second-tier institutions still produce work that is of relatively poor quality compared with their equivalents in Europe or America. "While China has fantastic quality at the top level, it's on a weak base," explains Caroline Wagner, professor of science policy at Ohio State University.

When it comes to basic, curiosity-driven research (rather than applied) China is still playing catch-up—the country publishes far fewer papers than America in the two most prestigious science journals, *Nature* and *Science*. This may partly explain why China seems to punch below its weight in the discovery of completely new technologies. Basic research is particularly scant within Chinese companies, creating a gap between the scientists making discoveries and the industries that could end up using them. "For more original innovation, that might be a minus," says Xu Xixiang, chief scientist at LONGi Green Energy Technology, a Chinese solar company.

Incentives to publish papers have created a market for fake scientific publications. A study published earlier this year in the journal *Research Ethics*, featured anonymous interviews from Chinese academics, one of whom said he had "no choice but to commit [research] misconduct", to keep up with pressures to publish and retain his job. "Citation cartels" have emerged, where groups of researchers band together to write low-quality papers that cite each other's work in an effort to drive up their metrics. In 2020 China's science agencies announced that such cash-for-publication schemes should end and, in 2021, the country announced a nationwide review of research misconduct. That has led to improvements—the rate at which Chinese researchers cite themselves, for example, is falling, according to research published in 2023. And China's middle-ranking universities are slowly catching up with their Western equivalents, too.

The areas where America and Europe still hold the lead are, therefore, unlikely to be safe for long. Biological and health sciences rely more heavily on deep subject-specific knowledge and have historically been harder for China to "bring back and accelerate", says Tim Dafforn, a professor of biotechnology at University of Birmingham and former adviser to Britain's department for business. But China's profile is growing in these fields. Although America currently produces roughly four times more highly influential papers in clinical medicine, in many areas China is producing the most papers that cite this core

research, a sign of developing interest that presages future expansion. "On the biology side, China is growing remarkably quickly," says Jonathan Adams, chief scientist at the Institute for Scientific Information at Clarivate. "Its ability to switch focus into a new area is quite remarkable."

The rise of Chinese science is a double-edged sword for Western governments. China's science system is inextricably linked with its state and armed forces—many Chinese universities have labs explicitly working on defence and several have been accused of engaging in espionage or cyber-attacks. China has also been accused of intellectual-property theft and increasingly stringent regulations have made it more difficult for international collaborators to take data out of the country; notoriously, in 2019, the country cut off access to American-funded work on coronaviruses at the Wuhan Institute of Virology. There are also cases of Chinese researchers failing to adhere to the ethical standards expected by Western scientists.

Despite the concerns, Chinese collaborations are common for Western researchers. Roughly a third of papers on telecommunications by American authors involve Chinese collaborators. In imaging science, remote sensing, applied chemistry and geological engineering, the figures are between 25% and 30%. In Europe the numbers are lower, around 10%, but still significant. These partnerships are beneficial for both countries. China tends to collaborate more in areas where it is already strong like materials and physics. A preprint study, released last year, found that for AI research, having a co-author from America or China was equally beneficial to authors from the other country, conferring on average 75% more citations.

Several notable successes have come from working together, too. During the covid-19 pandemic a joint venture between Oxford University's Engineering Department and the Oxford Suzhou Centre for Advanced Research developed a rapid covid test that was used across British airports. In 2015 researchers at University of Cardiff and South China Agricultural University identified a gene that made bacteria resistant to the antibiotic colistin. Following this, China, the biggest consumer of the drug, banned its use in animal feed, and levels of colistin resistance in both animals and humans declined.

In America and Europe, political pressure is limiting collaborations with China. In March, America's Science and Technology Agreement with China, which states that scientists from both countries can collaborate on topics of mutual benefit, was quietly renewed for a further six months. Although Beijing appears

keen to renew the 45-year-old agreement, many Republicans fear that collaboration with China is helping the country achieve its national-security goals. In Europe, with the exception of environmental and climate projects, Chinese universities have been effectively barred from accessing funding through the Horizon programme, a huge European research initiative.

There are also concerns among scientists that China is turning inwards. The country has explicit aims to become self-reliant in many areas of science and technology and also shift away from international publications as a way of measuring research output. Many researchers cannot talk to the press—finding sources in China for this story was challenging. One Chinese plant scientist, who asked to remain anonymous, said that she had to seek permission a year in advance to attend overseas conferences. "It's contradictory—on the one hand, they set restrictions so that scientists don't have freedoms like being able to go abroad to communicate with their colleagues. But on the other hand, they don't want China to fall behind."

Live until old, learn until old

The overwhelming opinion of scientists in China and the West is that collaboration must continue or, better, increase. And there is room to do more. Though China's science output has grown dramatically, the share that is conducted with international collaborators has remained stable at around 20% —Western scientists tend to have far more international collaborations. Western researchers could pay more attention to the newest science from China, too. Data from a study published last year in *Nature Human Behaviour* showed that, for work of equivalent quality, Chinese scientists cite Western papers far more than vice versa. Western scientists rarely visit, work or study in China, depriving them of opportunities to learn from Chinese colleagues in the way Chinese scientists have done so well in the West.

Closing the door to Chinese students and researchers wishing to come to Western labs would also be disastrous for Western science. Chinese researchers form the backbone of many departments in top American and European universities. In 2022 more of the top-tier AI researchers working in America hailed from China than from America. The West's model of science currently depends on a huge number of students, often from overseas, to carry out most day-to-day research.

There is little to suggest that the Chinese scientific behemoth will not continue

growing stronger. China's ailing economy may eventually force the CCP to slow spending on research, and if the country were to become completely cut off from the Western science community its research would suffer. But neither of these looks imminent. In 2019 we also asked if research could flourish in an authoritarian system. Perhaps over time its limits will become clear. But for now, and at least for the hard sciences, the answer is that it can thrive. "I think it'd be very unwise to call limits on the Chinese miracle," says Prof Marginson. "Because it has had no limits up until now." ■

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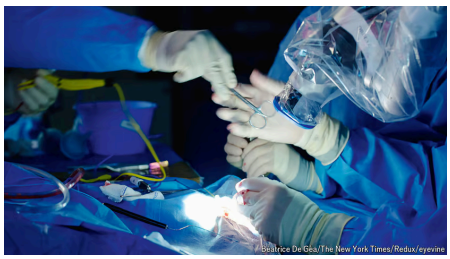

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