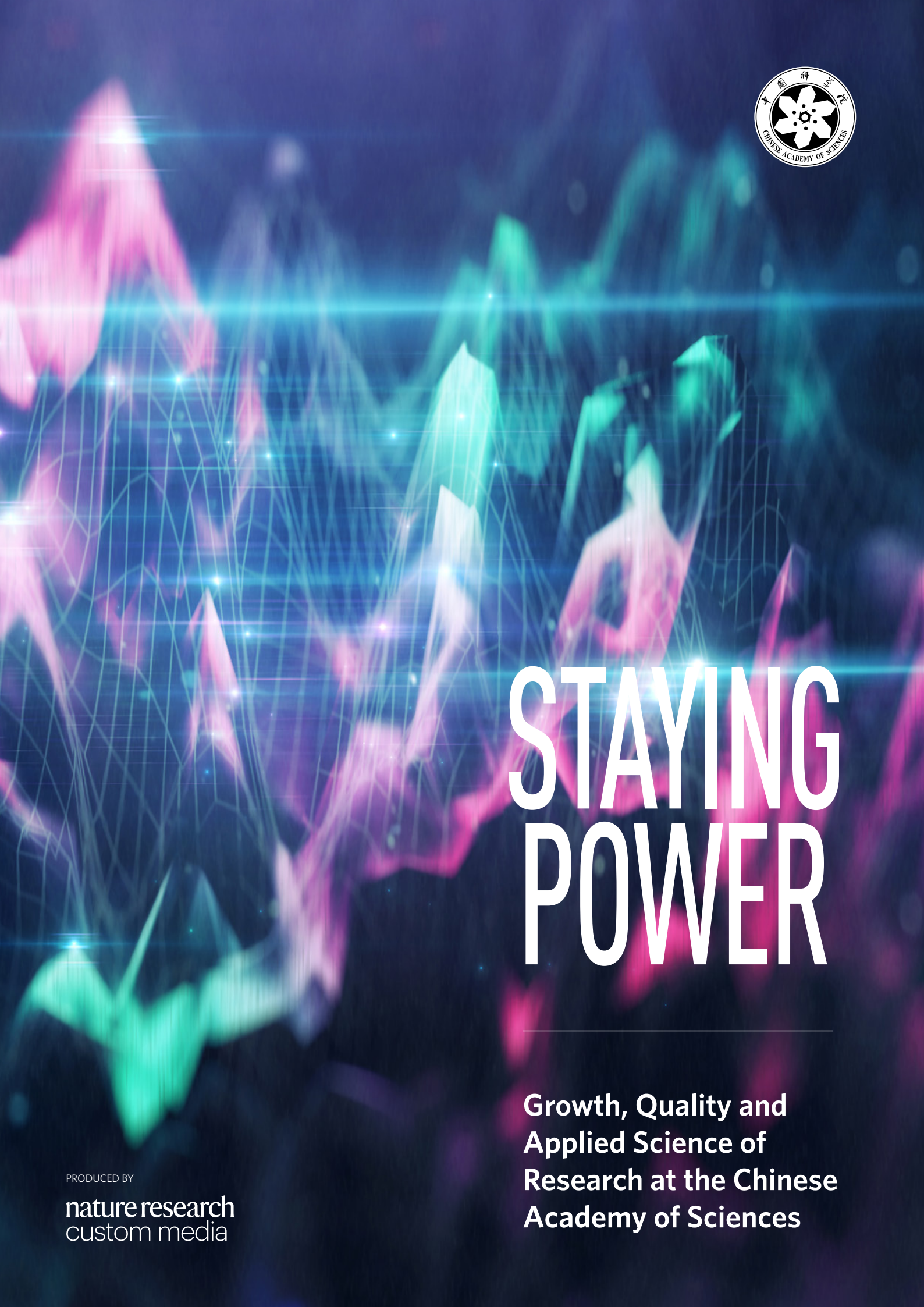

STAYING POWER

Growth, Quality and Applied Science of Research at the Chinese Academy of Sciences

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CONTENTS

EXECUTIVE SUMMARY

The Chinese Academy of Sciences (CAS) is one of the world's largest research organizations. Its output is not only a measure of Chinese research, but of global science and innovation. Over the past 10 years, CAS's output has grown continuously, both in total research output, and high-quality research. Moreover, CAS is diversifying its research output and growing fast in applied science fields.

Here are some key findings based on analysis of CAS's journal publications from 2008 to 2018, as tracked in Digital Science's Dimensions database:

- Chemical science papers dominate CAS's overall research output, with nearly 91,000 articles. Close behind is engineering, with more than 83,000 papers. The rest of the top five fields are biological sciences, physical sciences, and Earth sciences.

- Applied science fields have shown some of the strongest growth. Information and computer science is the fastest growing, with a compound annual growth rate (CAGR) of 18%. Medical and health science has a CAGR of 13% — both above the CAS average of 11%. Among CAS's top five fields, Earth science has grown the fastest.

- CAS's growth in high-quality science, as represented by the journals in Nature Index, is stronger than its overall growth. This is particularly evident in medical and health sciences, which have a CAGR of 19%. Biological science also grows faster in high-quality research than in overall output.

- For high-quality publications, chemical sciences remains the top field by volume, followed by physical sciences and engineering.

- In the sub-specialities of high-quality research, physical chemistry has the largest volume. Quantum physics has the highest concentration of high-quality research: around half of CAS's output is published in Nature Index journals. Oncology is the fastest growing subject with a CAGR of 32%. Case studies suggest CAS's efforts in developing applications based on these research strengths.

- In global comparisons, CAS's output exceeds that of the other 10 international research institutions in all but medical sciences, where Harvard University is leading.

- In high-quality research, the gap between CAS and other leading institutions has decreased. CAS has even lost its leading position in some fields, notably in some sub-specialities within the physical sciences, but is still leading in chemistry and engineering, by a large margin.

Whether research output can be transformed into real-world applications is another question. As CAS is developing its transformative research, fostering researcher innovation capacity is the key.

BIG HORIZONS FOR A GIANT OF SCIENCE

The Chinese Academy of Sciences supports more research and papers than any other research institutions. But is that research output translating into actual advances and real-world benefits? The data hold the answers.

CAS is exploring how to translate its growing scientific output into technologies and ideas.

Established in 1949, after the founding of the People's Republic of China, the Chinese Academy of Sciences (CAS) is the nation's most prestigious research institution. CAS researchers are dedicated to addressing both theoretical and applied problems. Their breakthroughs have contributed to China's rise as a research powerhouse, and have driven innovation in China and beyond.

CAS currently encompasses three universities and 100-plus research institutes across China. It leads the world in volume of scientific output, and has established research strengths in a number of science fields, including chemistry, engineering, biology, physics, and Earth sciences.

CAS's scale, coupled with decades of generous financial support from the government, have helped to drive the total number of papers. But does this translate into high-quality research? Does CAS exhibit balanced growth in all research fields? And how does CAS compare with the other leading research institutions around the world?

Science and technology also drive societal impact. To boost its capacity for innovation, CAS has launched new initiatives to restructure its institutes, optimize its management systems, and enhance international collaboration. This report will examine the patterns of growth in scientific publications over the past 10 years to see whether these initiatives have had an effect. While this is not a comprehensive assessment of innovation capacity, examining how CAS balances applied versus basic research and how it is diversifying its output gives a hint of how effectively CAS is addressing societal needs.

This report considers the volume and growth of CAS's research output, first, by broad research fields. It then drills down into high-quality research, as tracked by the Nature Index, and delves into research sub-specialities to identify areas of strength and growth potential. The report also compares CAS's research output with that of the world's other leading research institutions to assess where CAS leads and where it trails. These data analyses are accompanied by case studies on the outstanding specialities that account for the largest volume, the fastest growth, or the highest concentration in high-quality research output.

The aim is to identify CAS's research strengths and its growth patterns, particularly, in applied fields, suggest reasons behind the trends, and draw lessons for the future growth of CAS and of other research institutions. ■

DIVERSIFIED GROWTH

In recent decades, Chinese science has been characterized by fast growth and a dominance of chemistry over life sciences. These generalizations would seem to persist in CAS's research performance, but, a closer look suggests a trend towards diversification, with some applied research fields emerging as new strengths.

TOP RESEARCH FIELDS:
more than chemistry

The assessment of research output is typically, first, a volume game. This certainly gives an edge to an institution as large as CAS. According to journal publication data tracked in Digital Science's Dimensions database, CAS has published nearly 320,000 papers in the scientific literature from 2008 to 2018 — more than any other research institution in the world.

Looking at the broad fields, it is no surprise that CAS has published most in the chemical sciences, amounting to nearly 91,000 papers in 2008-2018. Engineering is the second most common field, with a cumulative total of more than 83,000 papers. As with chemistry, it accounts for more than one quarter of CAS's total output (Figure 1). Biological sciences papers are the third most common field, accounting for around 17% of output. Physical and Earth sciences round out the top five subjects.

The strength in the applied field of engineering might be surprising, given that CAS is usually considered a specialist in basic natural science research, but this is a misconception. CAS's research has always supported social development and industrial growth. Its research fuelled the development of China's first computer; led to the establishment of the country's internet information centre; and has informed a number of chemical engineering technologies, which in turn led to new drugs[1]. CAS research even helped to inform China's manned space mission.

In 2014, CAS put even greater emphasis on applied science. Responding to a national call for science and technology reform to better address industrial and economic development needs, CAS launched the Pioneer Initiative, part of which includes establishing a series of Innovative Academies. With a focus on mission-oriented research, these institutions, which are usually based on some existing CAS research institutes, seek to promote industrially applicable innovation in areas with commercial potential.

Dimensions data indicated that today 24 CAS institutes have an explicit engineering focus,

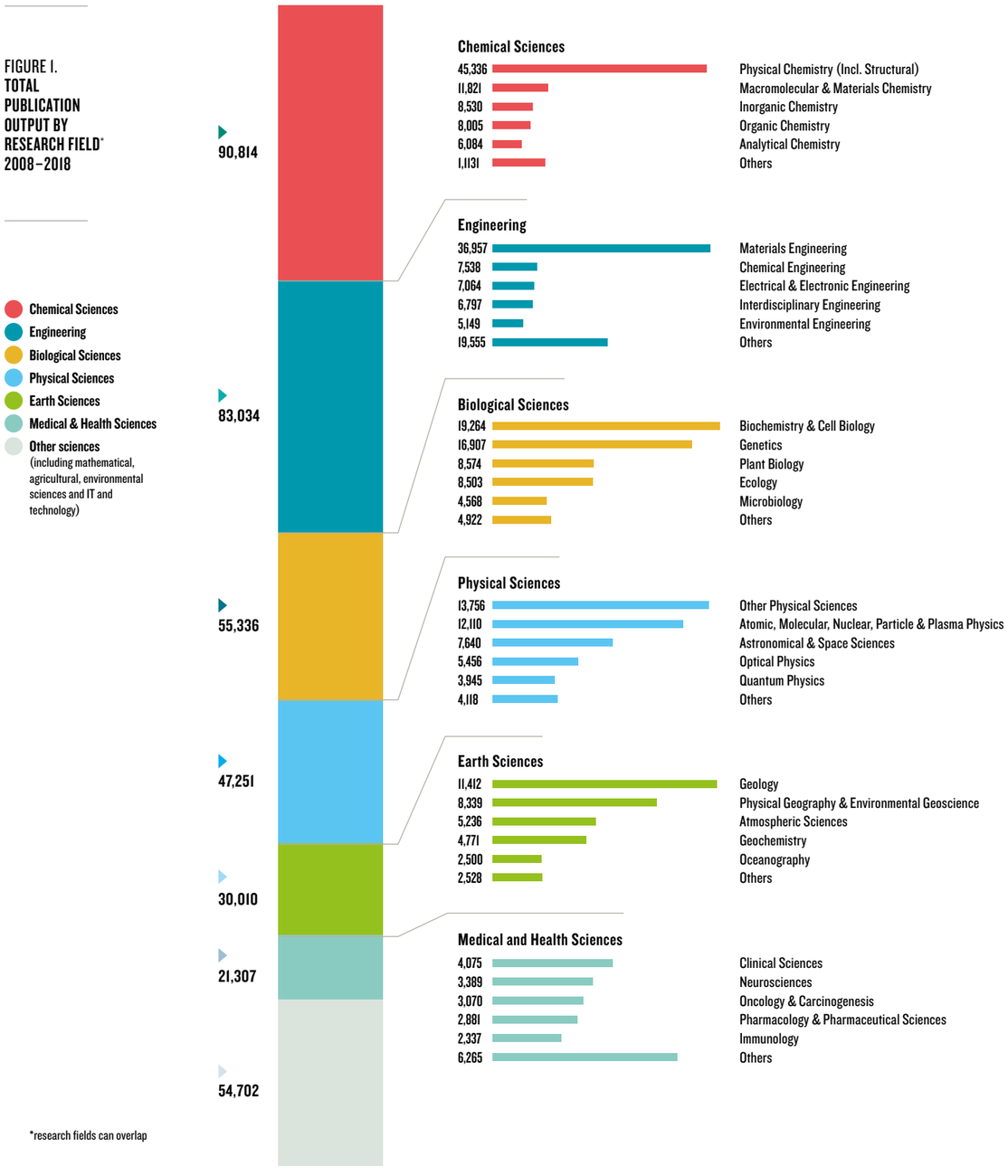
Engineering is CAS's second most published subject, and allies with the government's emphasis on industrial research.

including ones with a focus on microelectronics, mechanics, engineering thermophysics, remote sensing and digital earth, biomedical engineering, and space utilization technologies. They may also collaborate under the umbrella of CAS's Innovative Academies, both in research publications and commercialization.

In the realm of chemical sciences, China has a long history of strength, particularly in organic chemistry and synthesis. It has topped the Nature Index in organic chemistry since 2015[2]. Research from this field also plays a crucial role in many industrial processes with a number of uses, from synthetic drugs and food products, to polymer materials and catalysts for energy and chemical engineering industries. This helps explain why there might be only 10 CAS institutes with an explicit focus on chemical sciences, but the chemistry output is so big. In fact, there are many other CAS institutes, including those in physical, biological and medical sciences, as well as engineering, that also produce papers with a chemistry component, even if it is not their main focus.

By contrast, Dimensions identified 20 CAS institutes for biological sciences, suggesting an emerging emphasis on this field. Life science research is relatively new in China, and is still developing. A larger accumulative output of biological than physical sciences indicates a healthy upwards trajectory of research for the former.

FIGURE 1.
TOTAL PUBLICATION OUTPUT BY RESEARCH FIELD* 2008–2018



*research fields can overlap

STRONG GROWTH: potential for applied fields

Over the past 10 years, CAS's research performance is a story of growth. From a baseline of less than 16,000 papers in 2008, its output has nearly tripled to more than 46,000 papers in 2018, a compound annual growth rate (CAGR) of 11%. The highest growth rates are observed in several applied science fields, hinting at future potential.

CAS's fastest growth is in information and computing science, with a CAGR of 18%. The growth of the field came off a low baseline of only 450 papers in 2008, but it outpaces other fields with similarly low baselines. The finding points to the rising importance of information and computing science as central to China's high-tech industry, including the emerging field of artificial intelligence. While publication alone does not represent innovation capacity, the high growth is indicative of CAS's increasing potential to drive information technology innovations.

Medical and health sciences have also seen strong growth: output was below 1,000 papers in 2008, tripling to more than 3,300 in 2018, a CAGR of 13%. Growth in these applied sciences — allied with strength in engineering — aligns with the Chinese government's emphasis on research with immediate industrial application.

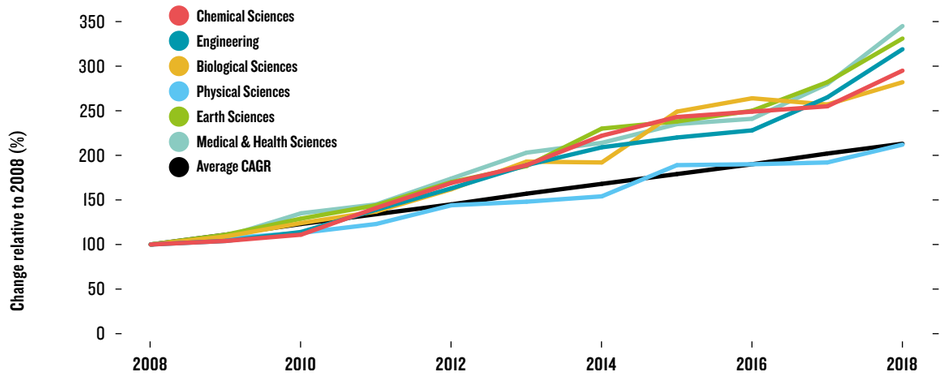
Of CAS's top five disciplines, Earth sciences, with the lowest baseline, have grown fastest, with a CAGR of nearly 13% over the past 10 years (Figure 2). This growth coincides with a Strategic Priority Research Programme ('Priority' programme) launched by CAS in 2012 for wide ranging geological, environmental/ecological investigations on the Tibetan Plateau. Among other elements, the programme has investigated how the India-Asia collision led to the formation of Tibetan Plateau, and how animals' evolution there diverged from those in other regions. By the end of 2015, the project had produced more than 500 papers[3].

To build on these discoveries, several CAS institutes, including the Institute of Tibetan Plateau Research and the Institute of Geology and Geophysics, established the Center for Excellence in Tibetan Plateau Earth Sciences in 2014. Such centres of excellence are part of CAS's efforts to strengthen its frontier sciences by bringing together its multidisciplinary resources.

Chemical sciences and engineering, the two fields with the largest volume of research, also have above-average growth rates, meaning they will stay dominant for years to come. Particularly, the strong growth of engineering reinforces the increasing weight of this applied field in CAS's research landscape.

Both physical and biological sciences have below-average growth rates, though the number of papers has risen overall. The percentage share of output for both these disciplines has also fallen, partly a reflection of the growing diversity in CAS's research output.

FIGURE 2.
YEAR ON YEAR PUBLICATION GROWTH RATE BY FIELD 2008–2018



HIGH-QUALITY RESEARCH: growth accelerated

Research strength is not just represented by quantity of output, but also quality. Nature Index is a curated list of 82 journals that serves as a proxy for high-quality research output. CAS's publications in Nature Index journals represented just over 8% of total output in 2008. By 2018, high-quality papers accounted for 12% of total output. The number of high-quality papers had more than quadrupled, growing at an adjusted CAGR of 13%, which is significantly higher than the CAGR for CAS's overall research.

In these Nature Index journals, chemistry accounts for more than 44% of all CAS's high-quality papers. Physical sciences are the second most common at around 34%. Engineering papers are only 16% of the total (Figure 3).

Applied subjects, such as engineering, are not as well represented in the life-sciences heavy Nature Index as in the general scientific literature. Much of the engineering in the Nature Index journals likely supports more advanced basic research. Given that CAS's high-quality engineering output is growing at an above-average rate, it follows that many of those innovations will be supporting growth in other areas of CAS's natural science research.

Of the top five broad fields, biological sciences have grown faster than the average for high-quality output (Figure 4). Given that biological science growth overall at CAS is low, this higher rate suggests that each additional paper in this field contains notable research. It is also possible that as the field is becoming more competitive, CAS researchers in biological sciences tend to aim only for high-quality publications.

An indicator of CAS's efforts to boost its high-quality biological sciences research is that, of the 13 established centres of excellence, three relate to biology, with focuses on molecular plant sciences, biological macromolecules and molecular cell biology. These centres employ cutting-edge biotechnologies, such as gene editing, to explore plant physiology and ecology, and to examine the molecular mechanisms of biological activities.

Outside the top five, one of the strongest growth rates is, once again, in medical and health sciences, with a 10-year CAGR of nearly 19%. Of all of CAS's medical and health science papers, those considered high quality have grown from less than 5% to over 9% from 2008 to 2018 (Figure 5).

This field, as with biological sciences, has benefited in recent years from increased funding. Health-related research, particularly in cancer, has become popular. Two of the three centres of excellence in biological sciences have put a greater focus on population health. Moreover, as more scientists return to China from countries such as the United States, their experience in life sciences and medical research has boosted CAS's ability to undertake and publish ground-breaking research in this field. ■

FIGURE 3.
RELATIVE PROPORTION OF HIGH-QUALITY RESEARCH OUTPUT 2008-2018

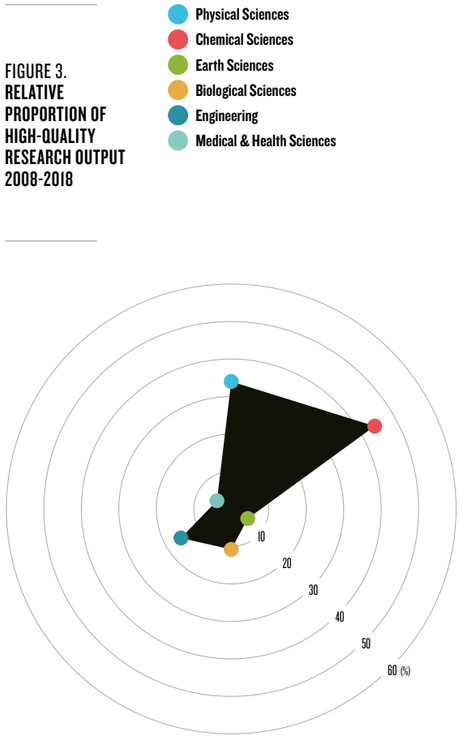


FIGURE 4.
VOLUME OF HIGH-QUALITY RESEARCH 2008-2018

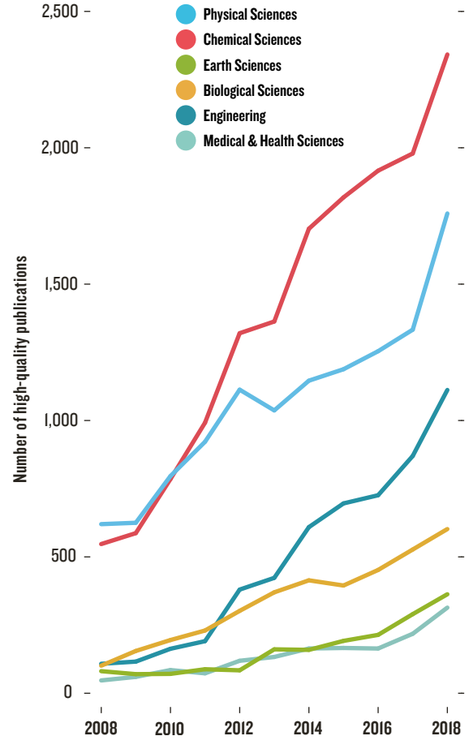
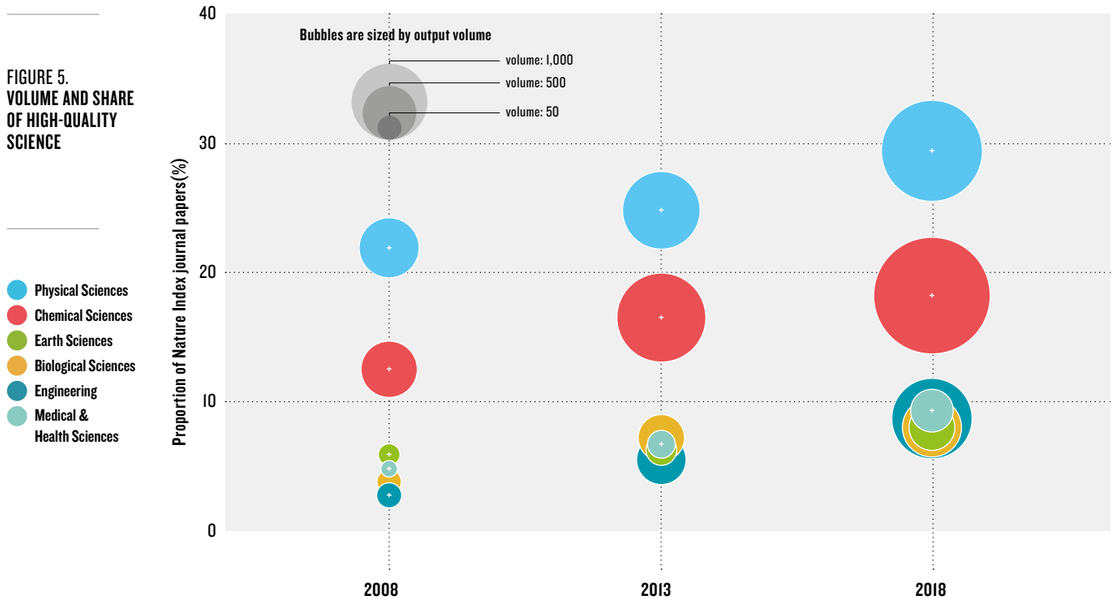


FIGURE 5.
VOLUME AND SHARE OF HIGH-QUALITY SCIENCE



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DETAILED RESEARCH ANALYSIS

A closer look at high-quality research output by sub specialities provides deeper insights into CAS's strengths. Here, basic science subjects, particularly in chemical and physical sciences, are still dominant, while applied subjects, in engineering and medical and health sciences, again exhibit the greatest growth.

In high-quality output, medical and health research is growing strongly despite not being a traditional strength for CAS.

TOP SUB SPECIALITIES BY HIGH QUALITY OUTPUT

Across all the sub specialities, CAS publishes most high-quality papers in physical chemistry (5,557 since 2008). Indeed, this is also the sub speciality with the largest volume of total output. Physical chemistry is the basis of many material engineering technologies, so has many applications in both basic research and society more broadly. The next strongest fields are in the physical sciences: atomic, molecular, nuclear, particle, and plasma physics (3,871 papers), and astronomical and space sciences (2,454 papers).

These basic science fields have also received increased numbers of external grants over the past decade. The physical subjects in particular require big science facilities, such as powerful particle accelerators and large radio telescopes. As part of the Pioneer Initiative, CAS has built Mega-Science Research Centers, which provide facilities and platforms for innovative basic research of strategic importance. The Daya Bay Neutrino Experiment, led by the CAS Institute of High Energy Physics, is an example of CAS's research capacity in this field. It involved several international partners and succeeded in measuring the third type of neutrino oscillation in 2012[1].

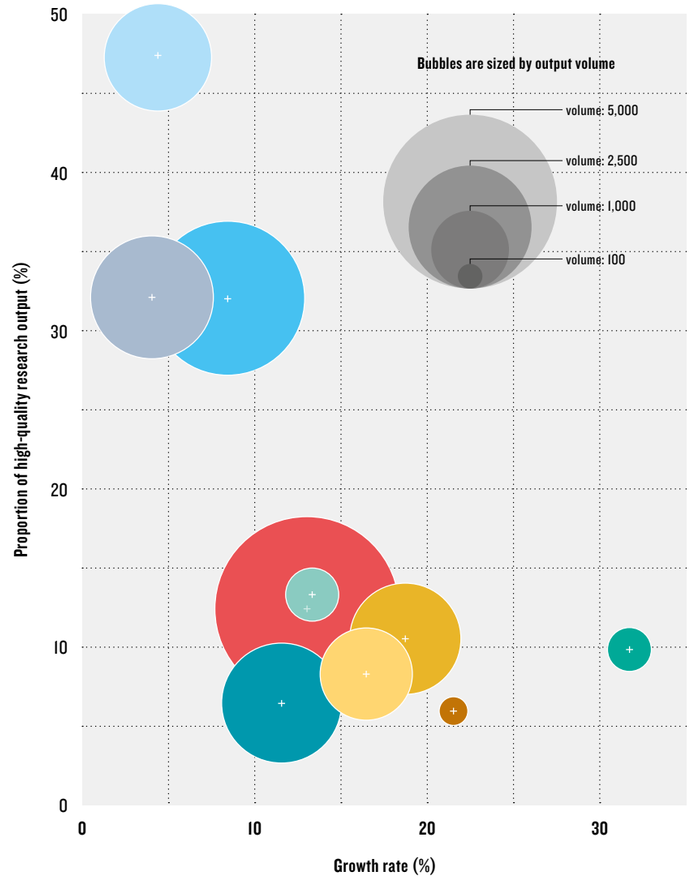
Materials engineering and biochemistry and cell biology also have more than 2,000 high-quality publications apiece. The latter accounted for more than half of all high-quality papers in the biological sciences and had a CAGR of nearly 19%, the second fastest in the field. Several biochemistry papers have come from the two recently opened centres of excellence, led by the Shanghai Institute of Biological Sciences (SIBS) and the Institute of Biophysics (IBP) in Beijing. IBP also led a 'Priority' programme studying biomacromolecules, which ran from 2014 to 2018. SIBS is leading another, ongoing 'Priority' programme that explores the molecular regulation of cell fate.

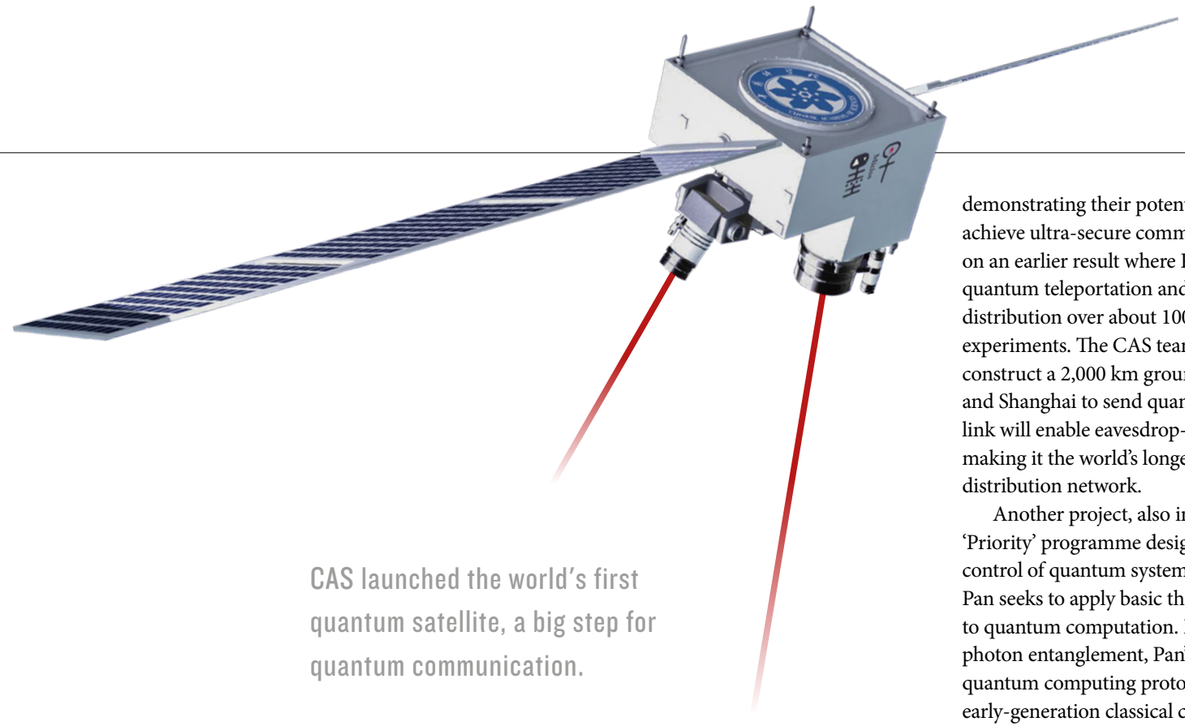
CONCENTRATION OF HIGH QUALITY RESEARCH

Another way to identify CAS's strongest research fields is to examine the percentage of high-quality research, namely, the proportion of the output of each sub speciality published in Nature Index journals. Here, several physical and chemical science subjects stand out, suggesting CAS's robust research capacity (Figure 6).

Quantum physics, in particular, has the highest concentration of high-quality research. Roughly one in every two quantum physics papers is published in a Nature Index journal, a proportion that has remained fairly stable over the past 10 years. Two other physical science subjects, astronomical and space sciences, as well as atomic and molecular physics, have around 33% of papers in the high-quality group. In addition, inorganic chemistry and organic chemistry, two traditional strengths of CAS, have around 17% papers in Nature Index journals.

FIGURE 6.
GROWTH RATE, SHARE AND VOLUME OF HIGH-QUALITY SCIENCE FOR SELECTED SUB-SPECIALTIES





CAS launched the world's first quantum satellite, a big step for quantum communication.

Quantum physics: Linking basic science and application

Quantum physics examines the fundamental energy and sub-atomic particles of the universe and it represents a growing opportunity for CAS. Thanks to generous governmental support, a number of large, strategically important frontier research facilities have been constructed in recent decades. CAS has turned this advantage into large numbers of high-quality publications and, crucially, into real-world applications.

The Quantum Experiments at Space Scale (QUESS)[2], which CAS initiated in 2011 as a 'Priority' programme is one such project. QUESS is led by Jianwei Pan from the University of Science and Technology of China (USTC), which was established by CAS in 1958, and it made headlines in 2016 when it launched the world's first quantum satellite.

Named Micius (or Mozi in Chinese), after the ancient Chinese philosopher, the satellite marked a giant step for quantum communication. Pan's team sent entangled photons from Micius to two ground stations more than 1,200 kilometres apart, demonstrating their potential as quantum keys to achieve ultra-secure communications[3]. This built on an earlier result where Pan's team demonstrated quantum teleportation and entanglement distribution over about 100 km in ground-based experiments. The CAS team has gone on to construct a 2,000 km ground link between Beijing and Shanghai to send quantum-encrypted keys. The link will enable eavesdrop-proof data transmission, making it the world's longest terrestrial quantum key distribution network.

Another project, also initiated by Pan, is a 2012 'Priority' programme designed to study coherent control of quantum systems. In that programme, Pan seeks to apply basic theories in quantum physics to quantum computation. By manipulating multi-photon entanglement, Pan's team developed the first quantum computing prototype, which outperformed early-generation classical computers in modelling photon behaviours[4]. "Our architecture is feasible to be scaled up to a larger number of photons and with a higher rate, to race against increasingly advanced classical computers," the authors wrote in a *Nature Photonics* paper[5].

Collaboration among CAS research groups, and between CAS and other universities, helps propel CAS's quantum research. One such example is the Center for Excellence in Quantum Information and Quantum Physics, established in 2014 as one of the first five CAS centres for excellence. Led by USTC, the centre includes interdisciplinary resources from the Shanghai Institute of Technical Physics and the Institute of Semiconductors at CAS. It also led the development of the quantum computing prototype alongside the CAS Institute of Physics, Zhejiang University and industry. Meanwhile, Pan's team is working with industry and local governments to commercialize research in quantum communication and quantum information.

To maintain its edge in quantum physics, CAS also embraced student education. As Pan said in an interview with *MIT Technology Review*[6], "we are working hard to develop the workforce of the future in quantum technology." And the capacity to integrate research and education also underlies CAS's success in research output.

HEALTH IS A GROWING CONCERN

When looking at growth, applied science subjects have the greatest potential. The highest-growth subject across all sub specialities, with a nearly 32% CAGR, is oncology and carcinogenesis. It is followed by electrical and electronic engineering, with a CAGR of almost 28%. Immunology and clinical sciences also have CAGRs above 20%. Though the total output over the past decade is not large, their fast rise suggests an increasing focus on health-related research, which is reflected in the broader Chinese scientific community.

Cancer research: A healthy growth

Medical and health sciences are not a traditional strength for CAS. Out of CAS's 100-plus institutes, fewer than 10 have an explicit medical science focus, a majority of which have been established since the turn of the century. However, this type of research is rapidly growing at CAS, and no subject is growing faster than oncology and carcinogenesis: the study of cancer, including its formation and treatment.

Breakthroughs in genomics, immunology and stem cell research have spurred the development of cancer therapies. At CAS, the central government's 'Healthy China' initiative, which emphasizes disease prevention, chronic disease management and high-quality treatment, drove efforts to translate basic research in fields like biological sciences, chemistry, and physics into medical and health innovations.

The focus on clinical application is explicit in a CAS 'Priority' programme initiated in 2016, which aimed at developing personalised drugs based on improved understanding of molecular mechanisms of diseases and genetic differences between patients. With developing cancer drugs as a major component, objectives were clearly set to identify biomarkers for drug targets, and obtain new drug certificates.

Led by the Shanghai Institute of Materia Medica (SIMM), in collaboration with other institutes at SIBS, and IBP in Beijing, this programme links basic research to clinical medicine. "In this billion dollar programme, we are trying to apply the concept of molecular typing for diseases to drug discovery," said Jia Li, the director of SIMM, at the 2019 Pujiang Innovation Forum[7].

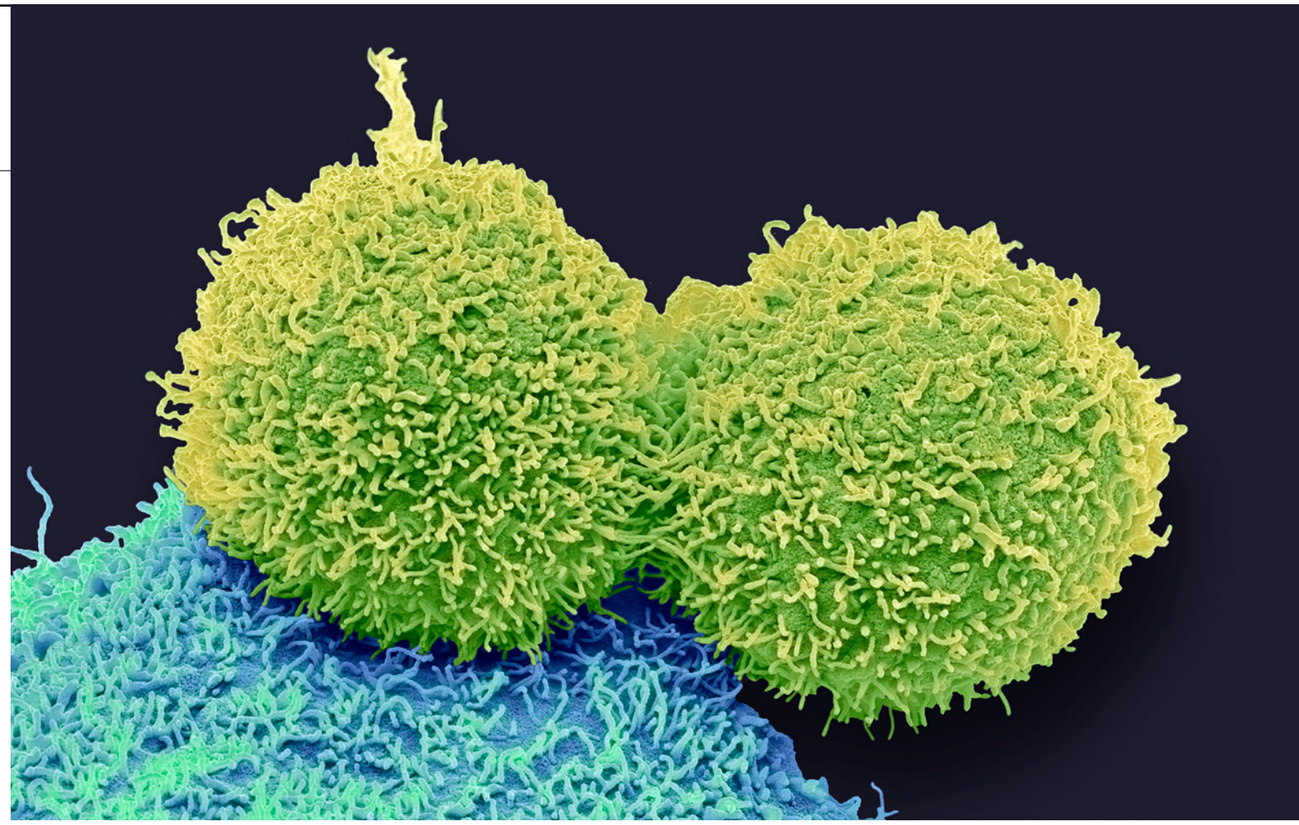
One representative result is a 2018 *Cell* paper, led by Meiyu Geng of SIMM, reporting potential of a precision treatment strategy for a specific kind of solid tumours by targeting epigenetic crosstalk[8]. The result may inform drug development for this tumour.

Apart from biological or health sciences-related institutes, other CAS institutes also contribute to oncology research. The National Center for Nanoscience and Technology (NCNST), for instance, is developing nanorobots to deliver cancer drugs. In this intelligent system, programmed DNA is folded when entering the bloodstream and unfolds at the tumour site to dispense a cancer-fighting protein[9]. "This breakthrough integrates nanotechnology with molecular biology," said Yuliang Zhao, director of NCNST who led this *Nature Biotechnology* study. "It will open a new realm for nanomedicine."

"THIS BREAKTHROUGH INTEGRATES NANOTECHNOLOGY WITH MOLECULAR BIOLOGY."

Much of CAS's oncology work is cross-disciplinary between physical science and biomedical researchers. NCNST researchers also use nanoparticles to improve cancer imaging, and to combine therapeutic and diagnostic action. Moreover, researchers at the CAS Institute of Physics work with hospital partners to develop improved probing techniques for cancer detection.

Further development of cancer research requires closer integration between CAS's many institutes and more cross-disciplinary collaboration between physical science and biomedical researchers, and even clinicians. Just as some nanoscience experts outline, the research should be guided by clinical need, as after all, the ultimate goal is to benefit cancer patients.



As cancer is becoming a leading cause of death, oncology research is booming globally and at CAS.

To promote such clinical application, CAS signed an agreement in early 2019 with the Zhejiang provincial government to establish the Institute of Cancer and Basic Medicine based on Zhejiang Cancer Hospital (which will itself be named the Cancer Hospital of the University of Chinese Academy of Sciences). As CAS's first dedicated cancer research institution, it will link basic, clinical and translational research, seeking to commercialize its results. Future growth in cancer research output is expected to follow, along with greater clinical benefits. ■

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CAS'S GLOBAL COMPETITIVE EDGES

Comparing CAS's output with that of its global peers, its traditional strength of chemistry is very evident. The comparisons also highlight many advantages enjoyed by large umbrella research organizations, which tend to lead in overall research output.

Chemical sciences is not only CAS's strongest subject, but is also the one where it is furthest ahead of the international competition.

CAS's overall output in the scientific literature has dwarfed that of the other leading international research institutions for the past decade. This gap is widening as CAS has a CAGR of 11%, the highest of its peer group. The second largest output is from Germany's Helmholtz Association with slightly under 119,000 papers, only around one third the output of CAS, and a much more modest CAGR of 8% (Figure 7). It is followed by Harvard University in the United States.

CAS has the highest output in all of the broad research fields with one exception: medical and health sciences. Here, CAS is seventh in terms of its 2008-2018 aggregate output, with Harvard in the lead. CAS is catching up, however, as it has the highest CAGR, at 13%. By 2018, it had already overtaken MIT, the University of Cambridge, and the Helmholtz Association, and currently ranks fourth in absolute annual output in medicine.

Medical and health sciences only accounts for 7% of CAS's overall research output, a big gap compared with 57% for Harvard University (Figure 8). As clinical research is not a traditional strength of CAS, there is still a catch-up role to play. But, as discussed earlier, the strengthening of biological sciences research and the national strategic push to promote population health have driven CAS's high growth in medical and health science research. CAS's heavy concentration on chemical sciences and engineering is also expected to become more balanced with this growing national push for population health.

FIGURE 7.
COMPARISON OF OUTPUT WITH 10 OTHER LEADING RESEARCH INSTITUTIONS

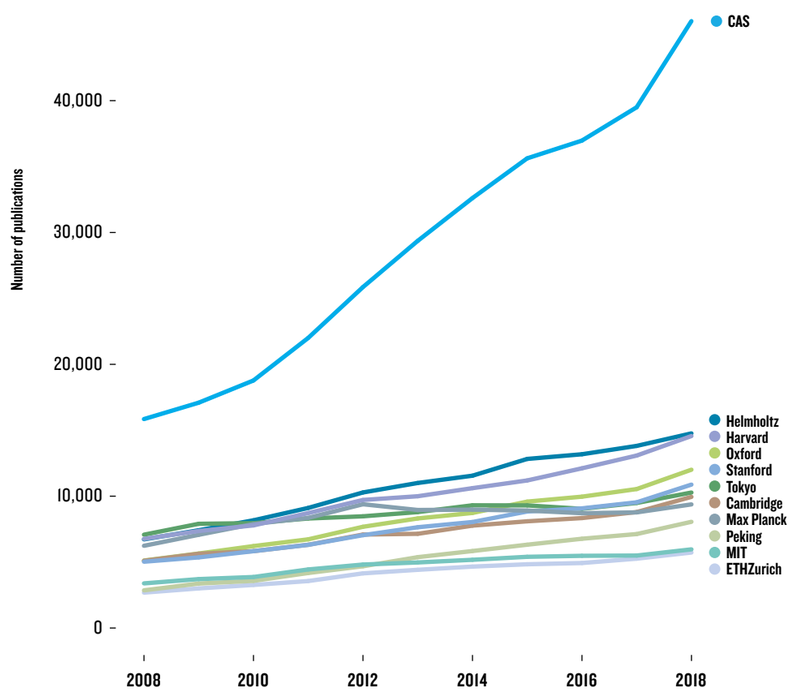
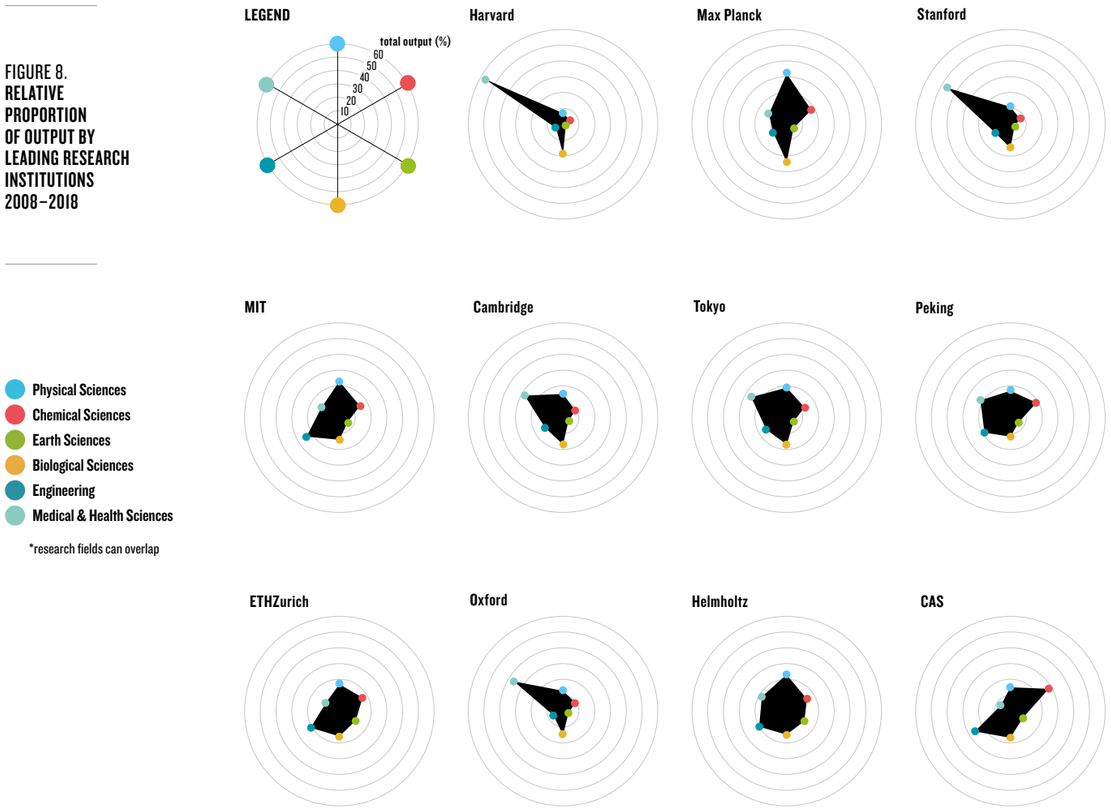


FIGURE 8.
RELATIVE PROPORTION OF OUTPUT BY LEADING RESEARCH INSTITUTIONS 2008–2018



COMPARISON AT THE SUB SPECIALITY

Drilling deeper into CAS's strengths, slightly different trends emerge. CAS leads the world in research output in the physical sciences overall. While that lead has not wavered in the past decade in the sub specialty of atomic and molecular physics, CAS is second in 10-year research output to the Max Plank Society in the astronomical and space sciences. That gap has recently closed though. Thanks to CAS's higher growth rate, its 2017 and 2018 research output was larger. Both institutions lead the Helmholtz Association, the third by volume, by a large margin.

In most of the medical and health sciences sub specialities, although CAS is not in the lead, it has narrowed the gap, particularly in neuroscience. From 2008 to 2015, CAS was in either sixth or seventh in this group. Since 2016, however, CAS has been publishing more, with the highest five-year CAGR. In 2018, its output exceeded that of close rivals, such as Max Planck, to be the fourth most prolific. Against the backdrop of the approval of the China Brain Project, CAS established a centre of excellence on brain sciences in 2014, which could well have contributed to this growth in neuroscience.

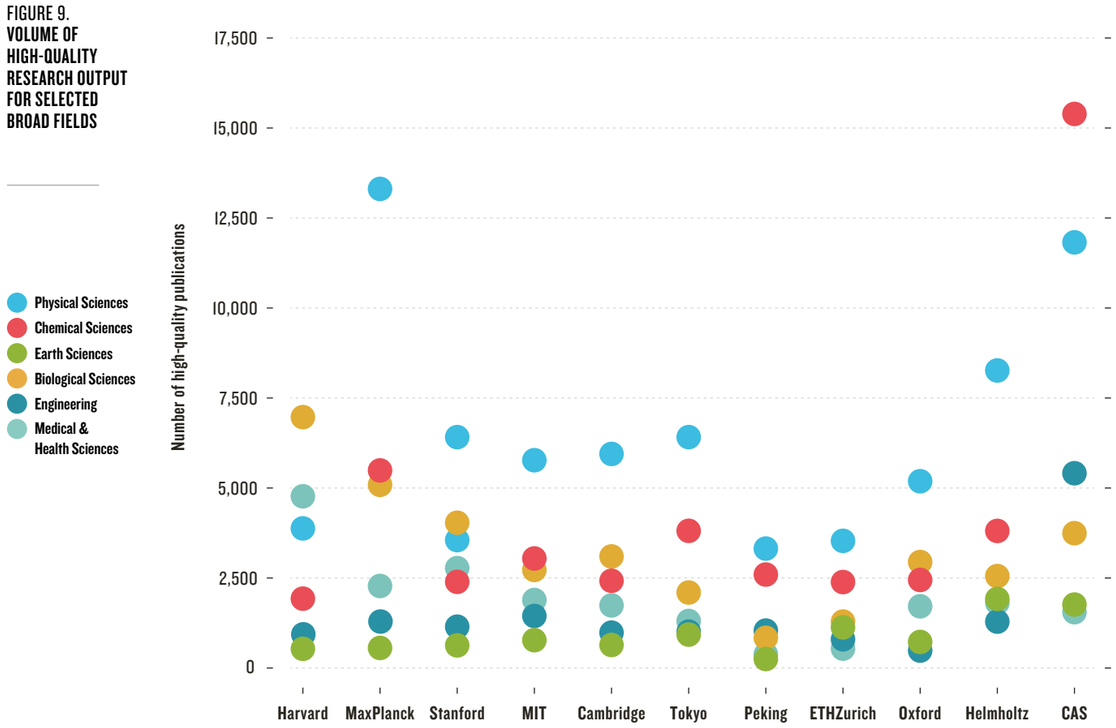
COMPARISON AT THE HIGHEST LEVEL

For high-quality science published in the Nature Index journals, the gap between CAS and its rivals is often much smaller, but not in chemistry and engineering (Figure 9). In chemistry, CAS not only dwarfs the output of the rest of the group, but is also growing the fastest, cementing its leading position. Max Planck publishes the second most overall, but in 2018 that was just over 600 papers compared to more than 2,300 at CAS. Engineering shows a similar pattern, with MIT in second place, having published just over 25% the number of papers as CAS in the past 10 years.

CAS loses its leading position in both mathematical and physical sciences though, where it is behind Max Planck for 10-year output. The latter is also growing more quickly than CAS.

In biological sciences, CAS's performance in high-quality publications is better than its general research output. Ten-year combined data show CAS in fourth, but it has the highest CAGR, and year-on-year has surpassed the other institutes, showing potential to achieve a leading position in annual output. From ranking ninth in 2008, it had overtaken Max Planck by 2018 with slightly more than 600 papers, behind only Harvard on 740.

FIGURE 9.
VOLUME OF HIGH-QUALITY RESEARCH OUTPUT FOR SELECTED BROAD FIELDS



Physical chemistry:

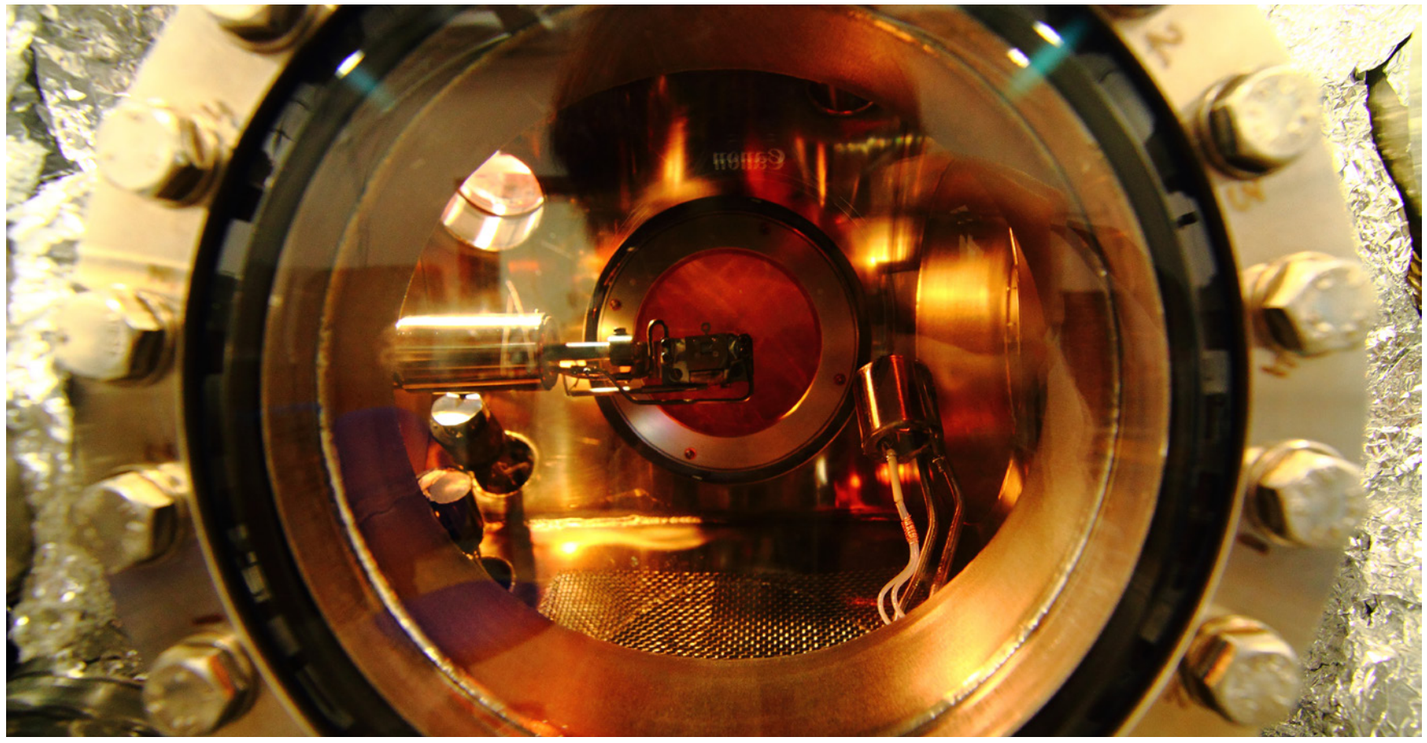
Chemistry is undoubtedly CAS's strongest field. According to the Nature Index, chemistry papers typically make up nearly half of CAS's research output in any given year, and CAS has produced the most chemistry papers of any institution worldwide for four consecutive years.

Within chemistry, CAS's strongest sub speciality is physical chemistry — the study of chemical systems using the theory and methods of physics. As such, it is widely applicable in both the chemical and physical sciences, as well as in industry.

"CAS is particularly strong in using physical chemistry techniques in topical and important areas such as sustainable energy development," explains Richard Catlow, a chemist at University College London, and foreign secretary of the Royal Society. He adds that CAS has "invested well both in people and in equipment and infrastructure" and consequently has "a number of world-leading physical chemistry labs".

One example is the Institute of Chemistry at CAS (ICCAS), which published 536 articles between 1 June 2018 and 31 May 2019, according to the Nature Index, being the highest publishing count of CAS's chemistry institutes. ICCAS houses three state key laboratories and eight CAS key laboratories, and specializes in organic/polymer materials, molecular science and nanoscience, energy, and green chemistry, many of which use physical chemistry techniques.

The CAS president, Chunli Bai, is himself a physical chemist who has published over 350 papers. Bai's research highlights include developing China's first scanning tunnelling microscope and atomic force microscope (AFM), important tools enabling the advances of Chinese nanotechnology. The AFM helped secure the first-ever image of the hydrogen bond. As revealed in a 2013 *Science* paper, scientists at the NCNST used non-contact AFM to observe hydrogen bonds between clusters of the flat organic molecule 8-hydroxyquinoline on a copper surface. "The present technique may provide an important and complementary characterization method for unravelling the fundamental aspects of molecular interactions at the single-molecule level," the authors said in their paper[1]. The work has been cited in the scientific literature more than 200 times.



The scanning tunneling microscope is an important tool that has enabled many nanotechnology advances.

CAS's physical chemistry research aligns strongly with industrial needs for alternative energy and green production. Scientists at USTC in Hefei published in *Nature* about a process to transform cobalt into a particularly active and robust electrocatalyst for turning waste carbon dioxide into a useful liquid fuel[2]. "Electroreduction of CO_2 into useful fuels represents a potentially 'clean' strategy for replacing fossil feedstocks and dealing with increasing CO_2 emissions," wrote the authors in this 2016 paper. The paper received global attention, and has been cited more than 600 times.

In promoting green chemistry, CAS scientists at the Institute of Metal Research (IMR) in Shenyang developed environmentally friendly refrigeration technology. In a recent *Nature* paper, they gave details of how the plastic crystal neopentylglycol behaves at the microscale when cooled[3]. The end goal of this field is to develop climate-friendly alternatives to hydrofluorocarbons for use in cooling systems. The work "paves the way to next-generation solid-state refrigeration technologies," wrote the authors.

EMERGING PATTERNS FOR SUB SPECIALTIES IN A GLOBAL COMPARISON

Delving deeper into the sub specialities, CAS's superiority in physical chemistry is overwhelming. However, in astronomical and space science, CAS has a way to go to top Max Planck for high-quality publications. The German group's output is also growing at a faster rate. It is clear that there is an intense global competition in this subject area and no institution can rest on its past achievements.

In medical and health sciences, CAS is quickly catching up in neuroscience, with the highest growth rate among the studied institutions. While for eight years from 2008, CAS was consistently eighth or ninth for neuroscience output in the Nature Index journals, starting in 2016, however, its high-quality output has grown more strongly, rising to fourth in 2018, behind only Harvard, Max Planck and Stanford. Its 10-year CAGR is 13%, but 16% for the past five years, an accelerating growth rate.

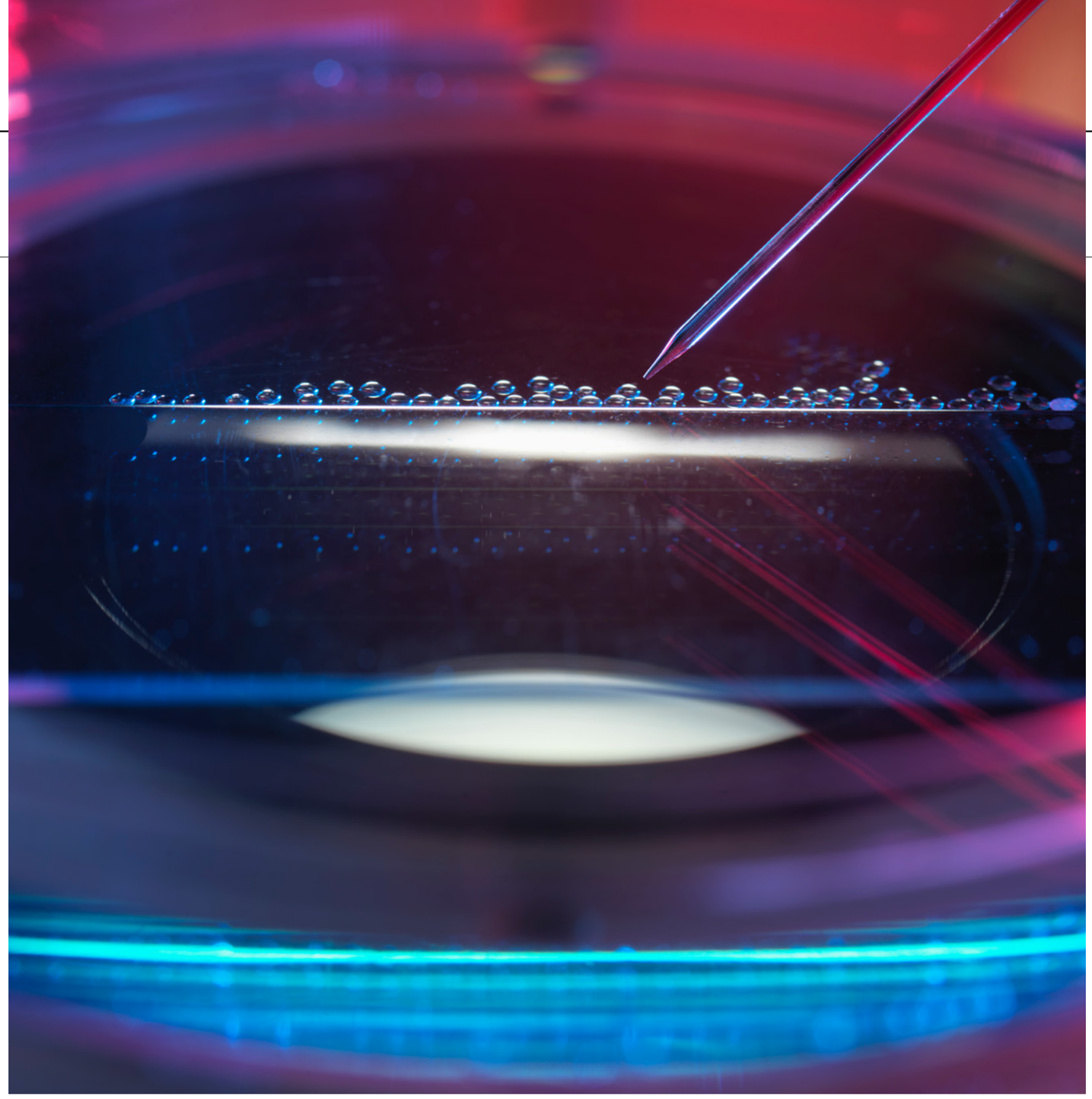
Again, this probably reflects the influence of the China Brain Project and the centre of excellence established to explore this field. Coinciding with this growth is a CAS 'Priority' programme launched in 2012, trying to map the brain connectome for a better understanding of the brain functions and intelligence. When the China Brain Project was approved in 2016, improving diagnosis and prevention of brain diseases was added to the agenda. The 'Priority' programme on brain science, led by the Institute of Neuroscience of SIBS and the Institute of Automation, was renewed after the end of its first phase in 2017, suggesting prospects for continued growth. As with other areas of medical research, CAS's willingness to mobilize cross-disciplinary resources, linking life sciences, medical sciences and information sciences, gives it a competitive edge in this increasingly interdisciplinary field. ■

References

1. Zhang et. al. Real-Space Identification of Intermolecular Bonding with Atomic Force Microscopy. Science, 342, 611-614 (2013)
2. Gao et. al. Partially oxidized atomic cobalt layers for carbon dioxide electroreduction to liquid fuel. Nature, 529, 68-71 (2016)
3. Li et. al. Colossal barocaloric effects in plastic crystals. Nature, 567, 506-510 (2019)

A BIG BALANCING ACT

When assessing research strengths, quality-versus-quantity is a persistent debate, as is basic-versus-applied research. CAS appears to be achieving a balance in both, with generally consistent patterns of overall and high-quality research performance and symmetry between its basic and applied research.



On the world stage, CAS's overall research output in the natural sciences is already formidable and is still growing. It has historical strengths in chemistry and physics, but in the past decade has started to diversify its research output. Notably, applied areas like medical sciences and information and computer science are growing fast, and engineering has overtaken physics to become CAS's strong field.

In high-quality science, CAS is growing even faster. Particularly, chemistry and engineering have an overwhelming edge compared with other top international research organizations. And the trend to diversify continues, with the strongest growth of medical sciences, particularly, cancer research.

Underlying these patterns is CAS's emphasis on transformative research or research with societal impacts. Chemistry and engineering, both of which have strong applications, represent the alignment of CAS's research with national strategic needs, as does the rapid growth of medical and health sciences.

As a large organization with a range of multidisciplinary research institutes, CAS has the capacity to mobilize resources across the disciplines to drive such strategic research. The 'Priority' programmes are good examples, which target science and technology issues of strategic importance and may well have boosted output in relevant subjects from quantum physics to neuroscience. Similarly, the establishment of Centres of Excellence, part of CAS's Pioneer Initiative to restructure the way it organizes research, also demonstrates its competitive edge in integrating its multidisciplinary fields to boost its strengths in frontier science fields, the effects of which are just starting to show.

A large, yet nimble organization, CAS has demonstrated the advantages of a research agglomerate: being able to quickly respond to the needs of growing frontier sciences, which are usually cross-disciplinary. As CAS strives to enhance its leading position, it also seeks to produce more breakthroughs for societal impact, to truly boost the science and technology innovation capacities of all its institutions, and of the nation.

However, there are also weaker areas in CAS's research development. CAS still has a lot to catch up in the medical sciences, although this area is growing fast. Moreover, it needs to further enhance its growth in high-quality research, and maintain its traditional areas of strength, such as physics.

Furthermore, publications are not the only indicator of innovation capacity. Whether the output in research can be transformed to real-world applications is another story. There is also a danger that CAS's heavy emphasis on applied research, or immediate applications, could impair the development of its very fundamental science, which may be the real engine that powers ground-breaking innovations.

Although a lot is said of the distinction between basic and applied research, and between the scientific disciplines, it is a continuum. Too much emphasis on their differences risks undermining interdisciplinary development. Research should be driven by the intrinsic curiosity of researchers, who are naturally attracted to questions that likely to make societal impacts. How best to foster and support such curiosity is the remit for research institutions like CAS. ■

CAS is diversifying its research strengths, playing catch-up in the medical sciences.

APPENDIX

Data and Methodology

This report uses journal publication data tracked by Digital Science's Dimensions database to assess CAS's research output from 2008 to 2018.

In Dimensions, Field of Research (FOR) codes are used to categorize journal publications. There are 22 broad research fields with 2-digit FOR codes, and 147 sub-specialities with 4-digit FOR codes. When an article does not have an abstract, or there is not enough text or information to assign it an FOR code, the article is given the FOR code of its journal. Some journals, normally interdisciplinary ones, only have a 2-digit FOR code. Therefore, the count of articles with a 2-digit FOR code is higher than the sum of articles with a 4-digit code. Also, one article can have multiple FOR codes.

FOR codes 1-11 are in the mathematical, natural and applied sciences, whereas 12-22 are humanities and social science subjects. As FOR codes 1-11 account for approximately 98% of CAS's total output, the analysis is focused only on these categories. Note that while the majority of publications assessed are primary research articles, Dimensions also tracks reviews, perspectives and sometimes news, which are all included in the analysis.

High-quality research output is represented by publications in Nature Index journals. These data are not taken from the Nature Index database, but from Dimensions, using the list of 82 Nature Index journals as the source. The journal list can be found on the Nature Index website: https://www.natureindex.com/faq#journals.

Using Dimensions produces some differences in the data. For instance, the Nature Index did not start till 2012, but the same journal list has been used to go back to 2008 to extract data for comparison purposes. Furthermore, reviews and other article types have been included alongside primary research papers. FOR codes are used instead of the Nature Index subject categories. And calculation of compound annual growth rate (CAGR) was normalized to compensate for the fact that the number of journals in the Nature Index has grown over the years.

Institutions used in the global comparison are selected from the top performers in Nature Index's annual tables.

REFLECTING ON 70 YEARS OF SCIENTIFIC SUCCESS

Established in 1949, the Chinese Academy of Sciences (CAS) is the nation's most prestigious research institution. For 70 years, it has been committed to advancing cutting-edge science and technology for the benefit of China and the world. It has played a pivotal role in China's rise to becoming a research powerhouse, and in driving science and technology innovation.

Housing three universities and 100-plus research institutes across the country, CAS is leading the world in the total volume of research output and breath of its subject areas. Many of its research results are the outcome of collaborative work with domestic or international partners. Breakthrough studies establish new frontiers, and address sustainable development goals that shape a better future.

Using research output data from the past 10 years, three reports will examine different aspects of CAS's research performance, painting a picture of its role and achievements.

RESEARCH STRENGTHS

Featuring CAS's research strengths, this report will examine patterns of CAS's growth in research output, identify subject areas where CAS is strong or has great growth potential. Does CAS have balanced growth in basic versus applied research? What drives this growth? Will CAS maintain its leading position in terms of high-quality research? By answering these questions, we can draw some lessons from CAS's success stories.

SCIENTIFIC COLLABORATIONS

Focusing on collaboration, this report will assess the importance of domestic and international collaboration in scientific discoveries. Does collaboration contribute to CAS's seminal growth in research output? What is the role of international collaboration in shaping CAS's global profile? We expect to demonstrate the importance of collaboration in CAS's success, and in scientific advancements in general.

ADDRESSING GRAND CHALLENGES

How does CAS's research output contribute to the UN Sustainable Development Goals(SDGs)? Where does CAS stand in addressing the SDGs compared with other leading institutions? By examining research output data and linking them to SDGs, we hope to show CAS's societal impacts, demonstrating the role of scientific discoveries in shaping a sustainable future.

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