SMALL SCIENCE IN BIG CHINA

An overview of the state of Chinese nanoscience and technology.

Conducted in collaboration between Springer Nature, the National Center for Nanoscience and Technology, China, and the National Science Library of the Chinese Academy of Sciences.
The National Center for Nanoscience and Technology, China

The National Center for Nanoscience and Technology (CN CST) was established in December 2003 by the Chinese Academy of Sciences (CAS) and the Ministry of Education as an institution dedicated to fundamental and applied research in the field of nanoscience and technology, especially those with important potential applications. NC CST is operated under the supervision of the Governing Board and aims to become a world-class research centre, as well as a public technological platform and young talents training centre in the field, and to act as an important bridge for international academic exchange and collaboration.

The NC CST currently has three CAS Key Laboratories: the CAS Key Laboratory for Biological Effects of Nanomaterials & Nanosafety, the CAS Key Laboratory for Standardization & Measurement for Nanotechnology, and the CAS Key Laboratory for Nanosystem and Hierarchical Fabrication. Besides, there is a division of nanotechnology development, with a responsibility for managing the opening and sharing of up-to-date instruments and equipment on the platform. The NC CST has also established 19 collaborative laboratories with Tsinghua University, Peking University, and the Chinese Academy of Sciences. The NC CST has doctoral and postdoctoral education programs in condensed matter physics, physical chemistry, materials science, nanoscience and technology. At the end of 2016, 4,039 post-reviewed papers were published. Moreover, a total of 868 patents were applied for, among which 393 patents had been authorized. In 2014, the International Evaluation Committee highly applauded the significant achievements and outstanding contributions in nanoscience, and remarked that NC CST had risen to a position of “by far the best in China.” In the Nature Index showed that NC CST has become one of the “Top 10 Institutes of CAS.”

In October 2015, CAS set up the Center for Excellence in Nanoscience (CAS-CENano) to accelerate the establishment of a new model for scientific research. The Center’s tasks are to accumulate innovative talent, focus on the frontier of nanoscience, to achieve major breakthroughs and become an international renowned organization.

The National Science Library, Chinese Academy of Sciences

The National Science Library, Chinese Academy of Sciences (NSLC) is the research library service system of CAS as well as the National Library of Sciences in Chinese National Science and Technology Libraries (NCNST) system. NSLC functions as the national reserve library for information resources in natural sciences, inter-disciplinary fields, and high-tech fields, serving the research and students of CAS and researchers around the country. It also provides services for information analysis, research information management, digital library development, scientific publishing (with its 17 academic and professional journals), and promotion of sciences.

NSLC is a key member of NSTL, it organizes research and training activities for strategic planning for STM libraries, digital library development, scientific publishing (with its 17 academic and professional journals), and promotion of sciences.

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FROM A SMALL SEED A MIGHTY TRUNK MAY GROW

A quarter of a century ago, Nature convened a meeting in Tokyo that brought together the world’s leading experts in a then emerging area of research that sought to understand and manipulate matter on the scale of atoms. They called it ‘nanotechnology’, though not everyone was happy with the name. Don Eigler, whose demonstration of the ability to spell the letters ‘IBM’ with individually-placed xenon atoms on a nickel surface produced one of the most iconic images of the field, expressed doubt about whether such a thing as nanotechnology even existed. Another delegate from IBM, Paul Horn, argued that the tools they had available to them were “wonderful tools for science” he didn’t expect them to have any impact on mainstream electronics technology any time in the coming 25 years.

In 1992, the study of objects at the nanometre scale — perhaps better described as nanoscience than nanotechnology — was carried out in just a handful of (mostly) physics or chemistry labs around the world. There were no journals devoted to the topic and barely half a dozen research institutes included the prefix ‘nano’ in their title. Today, there are 86 journals included under the category of ‘nanoscience & nanotechnology’ listed in the Journal Citation Report for 2016 published by Clarivate Analytics. And of the institutes currently listed in the Global Research Identifier Database maintained by Digital Science, 192 explicitly reference nanoscience or nanotechnology in their name.

Although it is true that we have yet to realize technologies that involve building things atom-by-atom, the caution urged by many of the founders of field has turned out to be pessimistic. Computer chips are now routinely manufactured with features that are just tens of nanometres in size, with IBM recently announcing the introduction of commercially produced chips with transistor features just 5 nanometres wide. The light emitting elements of many consumer televisions use nanometre-scale fluorescent particles known as quantum dots. Paints, sunscreens, medicines, sunglasses, pollution sensors, and gene sequencers are just of few of the many products that now use nanotechnology.

China recognized the potential contribution that nanoscience could make to its own scientific, technological and economic development, early on. In 2003, the Chinese Academy of Sciences (CAS) and the Ministry for Education together established the National Center of Nanoscience and Technology, China (NCNST). Key to the NCNST’s success has been the involvement of three of China’s most elite research institutions — Tsinghua University, Peking University and CAS. Over the past two decades, organizations like the NCNST, the other institutes of CAS, and China’s leading universities have helped to cement China to become the leading contribution to nanoscience and technology in the world today.

In this whitepaper, we have set out to give an overview of the state of nanoscience and technology in China today. In chapter 2, we try to set the scene with a brief history of the discipline and the milestones that have marked that history to date. We describe some of the ways in which nanoscience is changing the materials that make up our world, how we communicate, the development of new sources of energy and ways to make use of that energy more efficient, and how it is helping us to diagnose and treat diseases.

In chapter 3, we provide the hard numbers that plot the rise of nanoscience as a discipline and China’s rapid development to becoming a leader in that discipline. We will look at the output of nano-related research papers and in particular those that are making the strongest impact on the field. Using a recently developed nanoscience research platform developed by Nature Research known as Nano (http://nano.nature.com), we hope to provide qualitative insight into the nature of China strengths, weakness and areas of emergence in the field. And we will survey China patent output in related fields.

And in chapter 4, we will present what we have learned from talking to experts from the community about their thoughts on the current status and future direction of Chinese nanoscience. And we will explore the ways in which our experts think that their institutions, funders and policy maker might help to ensure the field continues to thrive.
THE PAST, PRESENT AND FUTURE OF NANOSCIENCE AND TECHNOLOGY

Nanoscience, in a nutshell, is the study of extremely small things on scales of between one and one hundred billionths of a metre—that is, 1-100 nanometres. At such small scales, the physical, chemical and biological properties of materials are very different to those at larger scales—often profoundly so. Alloys that are weak or brittle become strong and ductile, compounds that are chemically inert become powerful catalysts, semiconductors become intense emitters of light. The ability to change matter at the atomic level, and to manipulate it at the nanoscale, has implications by far beyond what we now call nanoparticle—indeed, all that is invisible to the naked eye. In the 1950s, Richard Feynman’s posthumously famous “There’s plenty of room at the bottom” speech at Caltech in 1959, as the birth of the field, in this Feynman notes that it should in principle be possible to write the contents of the entire Encyclopædia Britannica on the head of a pin, if it were possible to do so atom by atom. Yet this talk was cited only a handful of times in the immediate decades that followed. The term ‘nanotechnology’ itself didn’t come into existence until 1974, when Norio Taniguchi introduce it in his paper “On the Basic Concept of ‘Nano-Technology’” on the use of ion sputtering to etch nanoscale structures into hard surfaces. But the use of nanoscale materials can be traced back centuries ago, such as in the ceramic glazes and the decoration of stained glass windows. Almost a century before Feynman speculated on the potential of manipulating matter at the atomic level, British physicist and electromagnetic pioneer, Michael Faraday, already described the wavelength-dependent scattering of light (Tyndall scattering) by optically inactive gold particles of gold. He noticed what we now call nanoparticles of gold. He noticed the changed colour of gold colloids suspended in water, what we now call nanoparticles of gold. He noticed the changed colour of gold colloids and recognized the existence of tiny gold particles. It is one thing to appreciate the potential of being able to engineer the world atom-by-atom, but quite another to realize this potential. And in this sense, it has been the development of tools for seeing and manipulating matter that has determined the timeline of nanoscience and technology. The invention of the electron microscope by Ernst Ruska and Max Knoll in 1931 was the first tool to be developed—though it would take many decades of development before these devices would reach atomic-level resolution. But it was the demonstration in 1990 of the ability to spell the letters ‘IBM’ using individually-placed xenon atoms on a nickel surface by Don Eigler and colleagues using a scanning tunnelling microscope invented 9 years earlier by Gerd Binnig and Heinrich Rohrer that heralded the beginning of the age of nano into the public mind. It was also in the 1980s and 90s that researchers began pushing the limits of optics into the nanoscopic domain. The wavelength of visible light starts at around 400 nm, which according to classical understanding makes it incompatible with structures at the sub-100-nm length-scales associated with nanoscience and technology. In 1928, Edward Hutchinson Synge proposed the construction of a ‘near field’ microscope to beat the so-called Abbe diffraction limit that prevents conventional from resolving any structure smaller than about 250 nm. But it wasn’t until 1994 that Stefan Hell and Jan Wichmann proposed the first practical approach, known as stimulated-emission-depletion fluorescence microscopy, capable of optical imaging at the scale of molecules well below this limit. Improvements in our ability to study matter at the nanoscale initially led to the discovery of many naturally occurring nanostructures. In 1981, while studying the optical properties of semiconductor-doped glasses, Russian physicists Alexei Ekimov and Alexander Efros identified the presence of embedded nanoscale crystals that have subsequently come to be known as semiconducting quantum dots. Just a few years later, Louis Brus from the Bell Labs demonstrated the ability to grow these particles in solution. In 1985, Harold Kroto, Sean O’Brien, Robert Curl and Richard Smalley from Rice University in the U.S. discovered buckminster-fullerene (C60), a soccer ball-shaped molecule which is composed entirely of car-
One example is the inventions of nanotechnology. The early 2000s saw growing applications to incredible future technologies. In 2004, Andre Geim and Konstantin Novoselov in Manchester and colleagues invented a two-dimensional, one-atom-thick layer of carbon, which led to the development of the field of nanotechnology. This discovery of graphene, a single-atom-thick layer of carbon, has revolutionized the field of materials science, leading to the development of new materials with unique properties. These materials are used in coatings for machine parts, lubricants, reducing wear and tear and helping to extend the lifetime of machines. Nanostructured alloys, with their greater strength, high ductility and light weight, are ideal high-performance materials for airplanes and aerospace components. They are used for airframes, filler materials and other components, offering enhanced corrosion resistance, resilience to vibration and fire, as well as excellent weight-to-strength ratios. Nanoparticles of metals, oxides, carbon and other compounds also make good catalysts and have important industrial applications in petroleum refining and biomass fuels. With good surface-to-volume ratios, high catalytic activity and low energy consumption, nanocatalysis bring benefits such as optimal feedstock utilization, high energy efficiency, minimized chemical waste and improved safety.

Information technology

Nanotechnology has been a key driver that has powered the advancement of information technology and the digital electronics industry. It has enabled increased performance and miniaturization of electronic components, including computers, mobile phones and televisions. When Intel’s cofounder Gordon Moore proposed the famous Moore’s Law in 1965 that the number of transistors on a computer chip would double every year (later revised to every two years), nanotechnology was still in its infancy. Thanks to the development of nanotechnology, integrated circuits and transistors have become smaller and smaller as Moore predicted, while the computational speed is increasing, even though the Moore’s Law is still holding in recent years. In 2016, the world’s first one-nanometer transistor was born. Made from carbon nanotubes and molybdenum disulfide, rather than silicon, the nano transistor demonstrated the potential to further shrink electronics, keeping the Moore’s Law alive, at least a while longer. Deeper understanding of the physics of nanomaterials has promoted development of quantum devices, with applications in photodetectors, lasers and transistors, which allow high speed data transfer with lower power consumption. Nanomaterials are also used in a variety of products, ranging from lightweight and stiff tennis rackets to clothes that would double every year (later revised to every two years), recharges and storage capacity of future generations of batteries, it should reduce the weight of batteries and extend the efficiency and range of electric cars and other forms of transport.

Nanotechnology also finds applications in water treatment and contaminant clean-up. Membrane-based nanofiltration using molybdenum disulfide (MoS2) membranes have assisted water desalination and engineered the materials and structures on which they are based. For instance, the inclusion of quantum dots can enable these devices to absorb more light. And the use of materials such as conductive polymers and metal-organic frameworks that can be grown at low-temperature on inexpensive substrates offers a potentially cheaper alternative to conventional photovoltaic materials such as silicon.

Beyond assisting efficient harvesting of sunlight, nanomaterials can also be used to transform waste heat, such as car exhaust, into useful energy. For instance, nanoparticles that convert carbon dioxide into methane, a clean fuel gas, and new nanoparticulate photocatalysts that increase hydrogen production are developed, enhancing promises of alternative sources of renewable energy.

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Medicine and health

Arguably the most mature form of nanotechnology is that realized by life itself, the ability of our immune system to detect cells down to the operation of biomolecules such as...
1856: Observation of nanoparticles
Edward Hutchinson Synge observes gold colloids suspended in water.

1901: Quantum dots
Louis Brus reports synthesis of colloidal semiconductor quantum dots.

1928: Atomic layer deposition
Teoman Satoh invents atomic layer epitaxy for thin film growth technique.

1946: Atomic force microscopy
Gerd Binnig, Calvin Quate and Christoph Gerber invent the atomic force microscope.

1959: Quantum corrals
Michael Crommie, Christopher Lutz and Michael F. Crommie report the confinement of electrons by quantum corrals formed by iron atoms on a copper surface.

1968: Molecular self-assembly
Zivan, Biplov and Pickett report the self-assembly of well-ordered molecular monolayers on a surface.

1974: Nanotechnology coined
Norio Taniguchi coins the term “nanotechnology.”

1976: Surface-enhanced Raman spectroscopy
Martin Fleischmann, Patrick Henda and James McClellan report anomalous enhancement of Raman scattering, subsequently explained by Richard van Cittert and Alan Crommelt to be due to field-enhancement by nanorod metal structures.

1980: Observation of naturally occurring quantum dots
Alessi Ekimov and Alexander Efros report existence and optical properties of nanocrystal quantum dots.

1985: Buckyballs discovered
Harald Kröner, Sean O’Brien, Robert Curl and Richard Smalley discover fullerene (buckminsterfullerene) molecule.

1986: DNA nanotechnology
Zivan, Biplov and Pickett report the self-assembly of well-ordered molecular monolayers on a surface.

1988: Giant magnetoresistance
Albert Fert and Peter Grünberg report giant magnetoresistance in thin film multilayers.

1991: Carbon nanotubes
Semiclassical reports growth of carbon nanotubes. A year later Mike Drews and colleagues propose a theory that accurately predicts the ratio of metallic to semiconducting nanotubes.

1992: Molecular sieves

1993: Quantum cervices
Michael Crommets, Christopher Lutz and Ben Egler report the confinement of electrons by quantum corrals formed by iron atoms on a copper surface.

1996: Nanopore gene sequencing
Don Eigler and Erhard Schweizer demonstrate the use of an STM to manipulate individual xenon atoms on a nickel surface to form the letters “IBM”.

2001: Nanowire lasers
Peidong Yang demonstrates room temperature nanowire lasers.

2004: Isolation of graphene
Andre Geim & Konstantin Novoselov describe a technique for isolating individual sheets of graphene.

2006: Crystalline nanowires
David Leigh creates a molecular machine that acts as an artificial zipper to join together amino acids in a specific sequence.

2008: Giant magnetoresistance
Stefan Heil and Jan Wichmann describe a technique for optical imaging features below the diffraction limit by stimulated-emission-depletion fluorescence microscopy.

2013: Artificial ribosomes
David Leigh creates a molecular machine that acts as an artificial zipper to join together amino acids in a specific sequence.
...ribosomes, DNA, and ATP. These living systems are a source of continual inspiration for nanoscientists. Or, as synthetic biologist Tom Knight once remarked, “biology is nanotechnology that works!” As such, nanotechnology is having an increasing impact in the field of health and medicine, with steady progress in drug delivery, biomaterials, imaging, diagnostics, active implants and other therapeutic applications.

Perhaps the most remarkable development in the application of nanotechnology to biomedicine is the advent of so-called nanopore genetic sequencing. This method works by driving individual strands of DNA through a nanometre-sized hole in a thin membrane — or nanopore — using an electrical field. By measuring how the electrical current that flows through the nanopore as a strand of DNA passes through it, one can determine the sequence of genes that is encoded in the strand. This technology is expected to significantly reduce the cost and increase the speed of genetic sequencing.

Another promising medical application of nanotechnology is in drug delivery. Nanotechnology enables drugs to overcome chemical, anatomical and physiological barriers to reach diseased tissues, increases the accumulation of drugs at target sites, while reducing the damage to healthy tissues, bringing significant advantages over conventional medicines. For example, carefully designed nanomedicines are able to leak into cancerous tissues via leaky blood vessels and accumulate in target locations, offering higher precision of targeted cancer therapy. Additional applications include encapsulating biologically active molecules, such as antibodies, within nanoparticles to facilitate target-specific drug delivery.

Nanoparticles, given their small size and chemical properties, show particular promise for use in medical imaging. Conventional fluorescent dyes are made of organic compounds that are often short lived and whose optical properties are difficult to tailor to operate at arbitrary wavelengths. By using inorganic quantum dots whose operating wavelengths can be tuned by their size, both these limitations can be overcome. What’s more, they could be more easily designed to accumulate in specific tissues or tumour sites, enabling easier and better diagnoses and more effective treatment.

Nanotechnology has also found applications in tissue engineering. Nanomaterials such as graphene, nanotubes, and molybdenum disulphide can be used as scaffolds to help repair or reshape damaged tissue. Nanosstructured scaffolds mimic the tissue-specific microenvironment, facilitating cell adhesion, proliferation, and maturation, and fostering normal cell functions and tissue growth.

**Ethical and safety issues**

New technologies are like double-edged swords, bringing in both benefits and potential risks. Nanotechnology is no exception. Its rapid development, while much hailed, also deserves caution to the unintended environmental, health and social effects.

The biggest current concern is the threat of nanoparticles, which can easily enter body systems via our lungs or skin. For instance, contaminated metals in carbon nanotubes and diesel nanoparticles are found to have detrimental health effects. While worker exposure to nanopollutants during manufacturing processes is of high risk, consumers of nanotechnology-based products also face health risks. The use of nanomedicines, while promising, may also have unintended consequences, given the lack of understanding of whether or how they are metabolized in human bodies. The long-term effects of their use are still unclear.

Furthermore, industrial emissions during the production of nanomaterials and recycling of used nano-products cause contamination risks to the environment. The high reactivity and small size of nanoparticles may adversely affect the bio-ecological system, posing threats to plants and other animals. And as nanotechnology will dramatically alter the way we produce products, with molecular manufacturing as an example, and change the dimension of many commercial products, the economic impacts and societal upheavals that will incur are still unclear, which require careful judgement about the ethics of technology use.

In response to these various concerns, many governments around the world have taken actions. The US government has launched the National Nanotechnology Initiative, with supporting responsibilities for development of nanotechnology as one of its main goals, and organized several working groups to explore and address ethical, legal and societal issues of nanotechnology. In collaboration with the US, the European Union has also set up a platform to develop protocols to address emerging issues associated with the development of nanotechnology. The Chinese government has invested in nanosafety research since 2001, with around 7% of research budgets for nanotechnology flowing into scientific investigations of environmental, health and safety implications of nanotechnology. It also supports the development of standard methods to quantify the environmental and health hazards, as well as guidelines to monitor and regulate nanopollutants.

With careful consideration of the potential risks, nanotechnology can be harnessed to change our lives and environment in a desirable way. 2
Papers related to nanoscience and technology represented an ever-growing fraction of the total scientific output of most countries. For China, South Korea and India, that fraction is now well above the global average. In 2000, only around one-in-twenty nanoscience papers of the past decade have now been joined by S.Korea. These countries are now the largest contributor to the top 1% most-cited papers globally.

China’s share of the most-cited nanoscience papers increased at a higher rate year on year, than its total nanoscience output, with a compound annual growth rate of 22% — more than three times the global rate. It overtook the USA in 2014 and its contribution is now many times greater than that of any other country in the world.

**Chinese institutions lead the world**

Much of the progress in China’s rise to become the world’s leader in nanoscience over the past decade has been driven by the Chinese Academy of Sciences (CAS). Ten years ago, CAS’s contribution to the top-cited research was already impressive, ranking third in the world behind the USA and the United States Department of Energy.

Since then, its position has improved even further, to become the largest producer of high impact research by a wide margin. It now contributes more than twice as many papers in the 1% most-cited nanoscience literature than its closest competitors.

In addition to CAS, five other Chinese institutions are ranked among the global top 20 in terms of output of top-cited 1% nanoscience papers — Tsinghua University, Fudan University, Zhejiang University, University of Science and Technology of China and Peking University (see Figure 5).

The rapid growth of nanoscience in China has a lot to do with its consistent and strong financial support for research in the field. As early as 1990, the State Sciences and Technology Committee, the predecessor of the Ministry of Science and Technology (MOST), launched the Climbing Up project on nanomaterial science. Nearly a decade later, MOST funded a national structure basic research project and provided sustained funding in this area, boosting the research output of nanomaterials. During the 1990s, the National Natural Science Foundation of China (NSFC) also funded nearly 1,000 small-scale projects in nanoscience. In the National Guideline on Medium- and Long-Term Program for Science and Technology Development (for 2006–2020) issued in early 2006 by the Chinese central government, nanoscience was identified as one of four areas of basic research and received the largest proportion of research budget out of the four areas.

With the robust government funding support, a growing number of Chinese scientists have been attracted to nanomaterials research. The brain boomering, with more and more foreign-trained Chinese researchers returning from overseas, is another contributor to China’s rapid rise in nanoscience — a trend that is expected to continue into the foreseeable future.

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Chinese nanoscience, we turn now to the Nano database—a comprehensive platform that has been recently developed by Nature Research to help researchers keep up to date with the latest research in nanoscience and technology. The database includes detailed information on properties, applications and preparation methods of thousands of materials and devices extracted on a regular basis from the top 30 journals that publish nanoscience, including Science, Nature, Advanced Materials, Nano Letters and more (see Appendix 2 for the complete list). It was built by enlist ing the support of over 60 nanoscience experts to curate and categorize the information contained in the papers published in these journals. This knowledge was then used to train machine learning algorithms to automate the process and enable it to extract up to the minute information from research articles published in 167 peer-reviewed journals, in parallel to the manual extraction process. For the purposes of this whitepaper, we use the manually curated information that was used to construct the Nano database, which consisted of information extracted from the paper published in the corpus of 30 journals in the years 2014–2016.

Leading research areas in nanoscience

Analysis on the Nano database of nanomaterial-containing articles published 2014–2016 shows that Chinese scientists explore a wide range of nanomaterials, the five most common of which are nanostructured materials, nanoparticles, nanoscale devices and nanostructured materials and nanostructured devices. This is similar to the most popular nanomaterials observed in other research powerhouses (see Figure 6). It is worth noting that China has relatively higher research intensity on nanorobots and its papers on nanorobots have seen a soar in the past three years. For newly emerging nanostructures, defined as chemical engineering industry, according to some interviewed Chinese nanoscience experts. Many well-established Chinese chemists focus on research of catalytic materials and have fostered a group of younger generation researchers in the area, boosting the continued growth of research output in nanocatalysis.

Nanomedicine is the second largest area of China’s contribution to the research in the Nano database, particularly in the area of diagnostics. This might come as a surprise to some as both China and the research evaluation system plays an important role here, according to some interviewed Chinese nanoscience experts. Generally, national governments worldwide all tend to look for the application value of research output from countries. In China, with the robust government funding support to research, the guiding role of the government just tends to be amplified.

The role of collaborations

Collaboration draws in diverse scientific resources, expertise and perspectives and is becoming an important aspect in the research landscape. A notable feature of the Nano database is the analysis of the state of Chinese nanoscience and technology. It is notable for its high research output from 2014 to 2016 compared to other research powerhouses. But robotics and lasers are emerging applications areas of nanotechnology in China, defined as those not among the top 10 publications but enjoy high increase in research output in recent years. Moreover, nanoscience papers addressing photonics and data storage applications also see strong growth in China.

An overview of the state of Chinese nanoscience and technology

In contrast to the global trend but similar to Japan and South Korea, China has a higher rate of patent applications per SCI paper compared with the United States and most of the European nano research powerhouses. In the three Asian countries, nano-related patent applications usually outnumber their SCI publications, while it is the reverse in most western countries. Analysis using the Nano database tells the similar story. The fraction of papers listed in the database that explicitly mentions applications of the nanostructures and nanomaterials described was notably higher for research coming from China than most other leading nations, such as the United States, Germany, the UK, Japan and France (see Figure B). Only South Korea and Australia exhibited a similar trend. The guidance of the government funding policy and the research evaluation system plays an important role here, according to some interviewed Chinese nanoscience experts. Generally, national governments worldwide all tend to look for the application value of research output from countries. In China, with the robust government funding support to research, the guiding role of the government just tends to be amplified.

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An overview of the state of Chinese nanoscience and technology

Although patents are only a small part of the process of translating fundamental knowledge into commercial technologies, they are a leading indicator of the areas in which research is having a direct practical impact. Using nanoscience and technology-related patent data for the last 20 years, drawn from the Derwent Innovation Index (DII) database of Clarivate Analytics, we analysed the trends in the application of China’s nanoscience to China’s nanotechnology. A search by International Patent Classification codes and key words of 466,884 nanotechnology-related patent families from 1997 to 2016 (based on the earliest priority year, or basic patent application date) shows a global trend of rising patent applications related to nanotechnology. The number increased from around 2,826 in 1997 to more than 51,389 in 2015. The number of patents in China rises particularly fast and is leading the world now. Meanwhile, areas of nanotechnology-related patent applications cover a broad range in China, though with varying growth patterns. Consistent with its role as a research powerhouse in nanoscience, China has the largest number of nano-related patent applications in the world, which amounts to 209,344 for the cumulative total in the last 20 years, accounting for 45% of the global total. China’s accumulative total number of patent applications for the past 20 years is more than twice as many as that of the United States, the second largest contributor to nano-related patents. At a remarkable growth rate much higher than the world average, China surpassed the United States and ranked the top in the world since 2008 (see Figure 10).

Confident of their research or technologies, many Chinese researchers are also seeking international patent applications, the number of which is increasing steadily in China, from barely 10 in 2000 to 748 in 2014. However, the increase in international patents is not as fast as that of the total patent applications related to nanotechnology. Compared to other technologically advanced countries, the number of nano-related patents China applied overseas is still very low, accounting for only 2.61% of its total patent applications for the last 20 years accumulated, whereas the proportion in the United States is nearly 50%. And in some European countries, like UK and France, more than 70% of patent applications are filed overseas. Five Chinese institutions, including the CAS, Zhejiang University, Tsinghua University, Hong Kong University of Science and Technology, and Tianjin University have emerged among the global top 10 institutional contributors to nano-related patent applications. CAS ranks in the global top since 2008, with a total of 11,218 patent applications for the past 20 years. Interestingly, most of the other big institutional contributors among the top 10, like South Korea’s Samsung Group and LG Group, Japan’s Fuji Photo Film Co., Ltd and the United States’ IBM are commercial enterprises, while in China, research or academic institutions are leading in patent applications. This reflects the emphasis that Chinese researchers place on translating their research into applications and the relative strength of Chinese academic institutions in R&D. But it also highlights the relatively weaker role in R&D played by Chinese enterprises.

In the areas of electricity and electronics, chemicals and metallurgy, medicine, health, superfine techniques and materials, patenting activities in China have been growing consistently over the past 20 years, though at a much lower pace compared to those for semiconductors, the most common category for nano-related patents, which have been declining since 2012. Patents for superfine technologies rapidly increased in the first three quarters of the last 20 years, but declined after a peak in 2011. China has high numbers of patent applications in several popular technical areas for nanotechnology use, and is strongest in patents for polymer compositions and macro-molecular compounds. In comparison, nano-related patent applications in the United States, South Korea and Japan are mainly for electronics or semiconductors, with the United States leading the world in the cumulative number of patents for semiconductor devices (see Figure 11). This is generally consistent with the results from the analysis of applications mentioned in research papers included in the Nano database. Looking at the growth trend of China’s nanotechnology-related patent applications, polymer compositions and macro-molecular compounds are also the fastest growing areas. These may include paints, inks, dyes, adhesives and textile treating technologies or fibres. Patents for technologies or apparatus enabling chemical or physical processes, such as catalysis are also increasing fast in China.

FIGURE 10 | NANOSCIENCE PATENT OUTPUT. Number of patent applications in areas related to nanoscience and technology from 1997–2016 for top countries.

The rapid rise of China’s research output and patent applications has painted a rosy picture for the development of Chinese nanoscience. In both the traditional strength subjects and newly emerging areas, Chinese nanoscience presents great potential. But as with all newly emerging areas, Chinese nanoscience and technology. These include the Ministry of Science and Technology, the Ministry of Education and the NSFC, which are major research funding agencies in China. In the recent five years, Chinese universities have received more than 500 million RMB research budget on nanotechnology from the Ministry of Education alone. The CAS has also launched a Strategic Priority Research Program on nanotechnology with an investment of around 1 billion RMB. Specifically, great stock has been put into basic and applied research on nanomaterials, characterization techniques, nanodevices and manufacturing, catalysis and medicine. Several areas of nanoscience are identified by interviewed experts as most promising. **Opportunities**

With the promise of continued economic growth and the Chinese government’s commitment to support and promote innovation in science and technology, it is expected that investment in nanoscience and technology in particular will continue to grow. Relevant ministries and organizations under the Chinese state government have set up research plans to provide consistent funding in nanoscience and technology. These include the Ministry of Science and Technology, the Ministry of Education and the NSFC, which are major research funding agencies in China. In the recent five years, Chinese universities have received more than 500 million RMB research budget on nanotechnology from the Ministry of Education alone. The CAS has also launched a Strategic Priority Research Program on nanotechnology with an investment of around 1 billion RMB. Specifically, great stock has been put into basic and applied research on nanomaterials, characterization techniques, nanodevices and manufacturing, catalysis and medicine. Several areas of nanoscience are identified by interviewed experts as most promising.

**Catalysis**

Catalysis and catalytic nanomaterials are considered by several interviewed experts as a most promising nanoscience area for China. This is unsurprising given China’s already well-developed expertise in the field more generally. By speeding up chemical reactions, nanomaterial-based catalysts have wide applications in the chemical or chemical engineering industries, as well as the oil refining industry. The growing needs of industry continue to drive probably relatively easy; more focus needs to be devoted to finding novel methods for synthesis and better control of assembly. Also, the goal is not simply to publish more papers. “Are these [articles] really that important and [synthesized catalyst] really applicable in industry?” An expert pointed out that researchers need to ponder the value of the research and take China’s development of nanocatalysis to the next level.

**Energy**

The importance of energy and the need to develop renewable energy resources is widely recognized, particularly in China, where rising environmental problems have caused serious attention from the government. Chinese government’s dedication to long-term investment into new energy—study brings bright prospects for the development of nanotechnology in China. “The use of nanotechnology in the energy industry is very promising and we are likely to make big breakthroughs within the next five to ten years,” said a young expert in the field. China has the upstream of the solar energy industry, which benefits researchers doing new energy R&D with abundant resources. With the government’s strong capacity for mobilizing resources, China has an edge over the United States in developing nano energy technologies and popularizing renewable energy. Some of the nano energy research done in China is already leading the world, particularly in the development of lithium ion batteries. Recently, a Chinese team invented a foldable graphene oxide film-based device that produces de-
salinated water using solar energy, with minimized heat loss and high efficiency. And a number of groups around China are making important contributions to the development of low-cost, high efficiency perovskite-based solar cells.

**Innovation comes in different shades.** Chinese researchers are probably good at turning 1 to 10, but breakthroughs that turn from 0 to 1 are still rare and this is our challenge."

**Medicine**

As with energy, health and medicine are closely linked to everyone’s daily life, making nanomedicine a promising field. “The exciting thing for nanomedicine is the diagnostic and therapeutic features of it,” said an expert in the field. “By using nanotechnology, we can control drug release and better targeting.”

China’s large population base provides plenty of cases and patients for carrying out clinical studies, facilitating the development of translational nanomedicine research. In addition to the great potential of nanomaterials used for drug delivery and nanoparticles made into therapeutic drugs, the use of nanotechnology in medical devices and medical imaging is also an area that held high expectations for innovation. The lack of expertise in biologically inspired design could be a challenge, said another researcher. “As a key player in nanotechnology development, China is in need of improving research translation and industrialization, and keeping the investment channels open.” To me, basic research is to generate new knowledge, concepts, or theories, whereas applied research is geared towards applications and new products that make an impact. But now many people are doing something in between and there are lots of repeated research efforts because many people are just following the suit. I personally think we need to take the focus on applications.

Currently, the industry is involved to some degree. Many nanoscience researchers agree that the government needs to invest more in applied research to drive the translation of nanoscience research. “Support to basic nanoscience research provided by our government is relatively abundant now,” said one researcher. “But the investment in commercialization of research is still inadequate.” By applied research, he meant for R&D work that is aimed at developing new products or technologies. Some also invest heavily on R&D by establishing their own research arms. But this is not enough. The level of industry collaboration in Chinese nanoscience, indicated by the percentage of papers with industry coauthors, though increasing, is still not significantly different compared with other big research countries. As one nanoscience researcher said, “The government needs to further encourage the R&D work of enterprises and improve the system that facilitates translation of research.” It is recognized that real applications are driven by their scientific curiosity and need to be taken by product development and commercialization. This means that bridging the gap between fundamental and applied research is essential when highlighting the science and potential translation of research in China. Most of the world’s profound innovations originate from basic science discoveries. Yet, China is considered lagging behind in truly innovative research. To pave the ground for genuine innovation that goes from zero to one, more high-quality basic research is needed. As one researcher noted. “There are lots of discussions on applications now, but [we] also need to do more basic research to understand the fundamental structures of different nanomaterials and better control the structures.” Indeed, that is what ultimately drives development of new catalysts, efficient solar cells, or novel drug delivery approaches.

**Challenges**

The prospects are promising and there is also an area that held high potential for China’s nanotechnology development. This is a long-term task and researchers advised that the process of industrialization needs to be taken step by step and that caution needs to be taken against seeking instant benefits. It is good news that the Chinese government is committed to funding the entire development chain of nanotechnology. To scale up the societal impacts of their research, scientists should play a more significant role in guiding the direction of the funding, as with the knowledge of cutting-edge science, they have better prescience of disruptive technologies compared with industrial leaders or policy makers.

**Balancing applied and basic research**

Achieving research translation and making positive impacts are the goals of nanotechnology development, but fundamental research is still the basis and fuels application. For most scientists at universities or research institutes, their research activities should still be driven by their scientific curiosity and need to be taken against the balance between fundamental and applied research. The goal of basic research is to find what we don’t know yet, whereas applied research is about developing technologies that can be converted into impact. But now many people are doing something in between and there are lots of repeated research efforts. One researcher noted, “There are lots of discussions on applications now, but [we] also need to do more basic research to understand the fundamental structures of different nanomaterials and better control the structures.” Indeed, that is what ultimately drives development of new catalysts, efficient solar cells, or novel drug delivery approaches.

"Innovation comes in different shades, Chinese researchers are probably good at turning 1 to 10, but breakthroughs that turn from 0 to 1 are still rare and this is our challenge."
Nanoscience is very broad and is interdisciplinary in nature, which is in line with the global trend of integration of different scientific fields. There should be more cross-disciplinary collaboration.
Fifty years ago, the idea of manipulating the material world at the nanoscale seemed like a fantasy. Twenty-five years ago, even those who were inventing the tools to turn this vision into reality did not believe those tools would lead to commercial nanotechnologies as we know them today. Today, machines that sequence genomes by threading individual strands of DNA through nanowires are commonplace. But such rapid growth brings inevitable challenges.

Although it was founded by physicists and chemists, nanoscience has evolved into a field that is intrinsically interdisciplinary, intrinsically broad and intrinsically collaborative. The pace of progress in the field relies on being able to draw on the expertise of researchers from many different disciplines. This in turn relies on physicists, chemists, biologists, material scientists, clinical researchers and engineers developing a common language. In this way, nanoscience is not only driving research for its own sake — not least for the unexpected, world-changing discoveries that this type of research regularly produces. But the consensus of the experts we talked to while researching this whitepaper suggest that there is more to be done to bridge the gaps between basic science and applied science, and between applied science and its development into practical solutions. Finally, the most common theme in the discussions we had with our experts — and the most important one for the future of Chinese nanoscience — is their expectation that the most potent source of innovation in the field is the next generation of Chinese nanoscientists. This will be no surprise to funders such as the NSFC, who have already taken a lead in this with funding programmes that are specifically targeted at young scientists. But adequate funding is just one part of the picture. Education is just as important, and one in which the NCNST and other institutions in China are addressing through the development of dedicated curricula that equip students with a wider variety of skills that they might not get from more traditional physics, chemistry or biology programmes.

Introduction to the Nano database

Nanoscience, as known, was launched in June 2016 as a non-journal platform under the Nature Research portfolio. It aims to provide highly indexed and structured information related to nanoscience and technology, including detailed descriptions of thousands of different nanomaterials and devices, their physical, chemical and biological properties, their potential uses and the various methods and protocols by which they have been prepared. The data are derived from articles published in peer-reviewed journals, compiled from many different sources, and are made into manually curated nanomaterial summaries. Here, a nanomaterial is defined as any material that typically consists at least one feature with a dimension in the range of 1 to 100 nm. In parallel, data indices are generated by machine learning algorithms that scan over 167 journals including leading titles from Springer Nature — whose brands include Nature Research, BioMed Central and Springer — and other publishers including AAAS, Elsevier and Wiley, on a regular basis. For this whitepaper, nanomaterial summaries that contain information on properties, synthesis and application are manually extracted and curated by nanoscience experts from nearly 30 journals (see below for the full list) that are recognized as highly impactful to the nanoscience research communities.

These manually extracted data obtained from papers publishing in these 30 journals from 2014–2016 were analysed to provide insights of the nanotechnology experts from primarily 30 journals (see below for the full list) that are recognized as highly impactful to the nanoscience research communities. The analysis of the Web of Science and Derwent Innovation Index data was conducted by the National Science Library, Chinese Academy of Sciences, while the analysis of the Nano data was conducted by Nature Research staff.

Appendix 1 | Data collection methodology

This paper uses both quantitative analysis and qualitative information to assess the trends of China's development in nanoscience and nanotechnology, and to identify opportunities and challenges. The quantitative analysis uses Nano data developed by Nature Research and Web of Science citation data as well as the Derwent Innovation Index data, both from Clarivate Analytics to examine nano-related research output and patent applications.

Specifically, a Topic search using nanoscience and nanotechnology-related key words in articles of the Science Citation Index (SCI) database, with copyright years of 1997 to 2016, resulted in 3,372,610 papers. The cut-off date for data retrieval is June 16, 2017 and terms used for the search include nano, self-assembly, atomic simulation, molecular electronics, quantum dot, atomic force microscope, scanning tunneling microscope and many others. Year-by-year changes of nano-related research output from 1997 to 2016 are analyzed at the world level and for key countries that are major contributors of nano-related papers. The key word search is also applied to the Derwent Innovation Index, a comprehensive database of patent information compiled from more than 40 patent-issuing authorities worldwide, in combination with a sorting by the international patent classification codes. Altogether, 466,884 nano-related records of patent families with application years (referring to priority years) of 1997 to 2016 are retrieved. The cut-off date of data retrieval is June 9, 2017. The analysis of the Web of Science and Derwent Innovation Index data was conducted by the National Science Library, Chinese Academy of Sciences, while the analysis of the Nano data was conducted by Nature Research staff.

Furthermore, qualitative data are collected from a roundtable discussion and several individual interviews or conversations with nanoscience experts active in China's academic community for insights about challenges and opportunities in China's development of nanoscience and technology. The roundtable discussion was organized with the support of National Center for Nanoscience and Technology, Chinese Academy of Sciences at the 12th Sino-US Symposium on Nanoscience and Technology held in the end of May, 2017. Individual interviews were conducted via phone by Nature Research staff in early June, 2017.

Appendix 2 | Journal titles covered for this analysis

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<th>Publisher</th>
<th>Journal</th>
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<td>AAAS</td>
<td>Science</td>
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<td>ACS</td>
<td>ACS Nano</td>
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<td>ACS</td>
<td>Chemistry of Materials</td>
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<td>ACS</td>
<td>Journal of the American Chemical Society</td>
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<td>ACS</td>
<td>Nano Letters</td>
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<td>APS</td>
<td>Physical Review Letters</td>
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