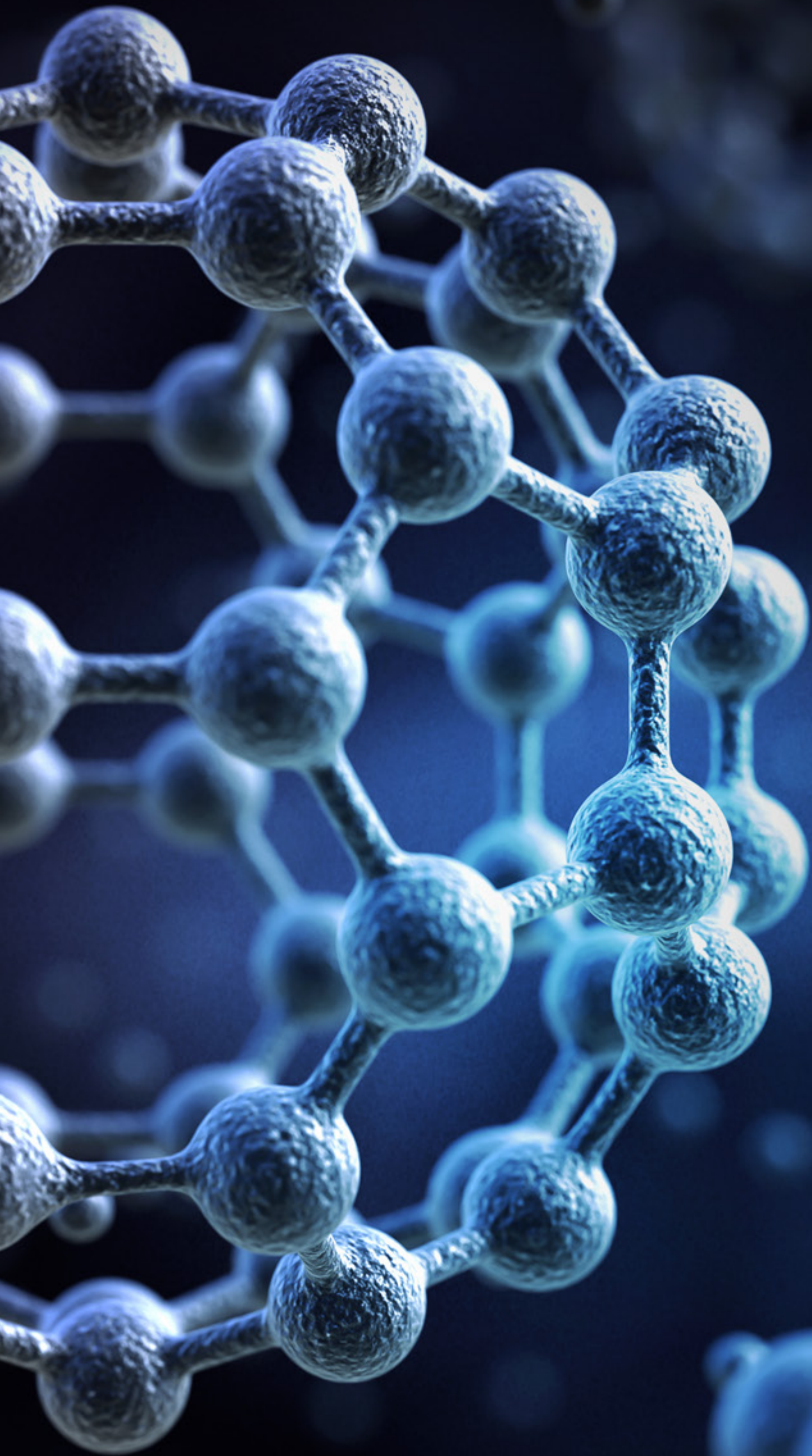

SMALL SCIENCE IN BIG CHINA

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.

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The National Center for Nanoscience and Technology, China

The National Center for Nanoscience and Technology, China (NCNST) was established in December 2003 by the Chinese Academy of Science (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. NCNST is operated under the supervision of the Governing Board and aims to become a world-class research centre, as well as 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 NCNST 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, which is responsible for managing the opening and sharing of up-to-date instruments and equipment on the platform. The NCNST has also co-founded 19 collaborative laboratories with Tsinghua University, Peking University, and CAS.

The NCNST has doctoral and postdoctoral education programs in condensed matter physics, physical chemistry, materials science, and nanoscience and technology. At the end of 2016, 1699 peer-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 NCNST had risen to a position of “by far the best in China”. In 2016, the Nature Index showed that NCNST 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 internationally 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 the Chinese National Science and Technology Libraries (NSTL) system. NSLC functions as the national reserve library for information resources in natural sciences, inter-disciplinary fields, and high-tech fields, serving the researchers and students of CAS and researchers around the country. It also provides services in information analysis, research information management, digital library development, scientific publishing (with its 17 academic and professional journals), and promotion of sciences.

NSLC is proactively leading national efforts to build a shared National Scientific Information Infrastructure. As the key member of NSTL, it organizes research and training activities for strategic planning for STM libraries, digital library standards, knowledge organization systems, digital preservation technologies and practices, and open access policies, in addition to provision of STM information nation-wide. It collaborates with major domestic and foreign libraries for resources sharing and research in library and information services.

NSLC is credited, under the auspice of CAS University, to offer master and doctoral degree programs in library and information sciences, with a yearly enrolment of about 50. The library also hosts senior visiting scholars and organizes vocational training and continuing education programs. It is one of the most published and cited research organizations in library and information sciences in China, and the hosting institute for the China Society of Special Libraries.

NSLC, aiming at developing a world first-class information service ability and leadership in library development in the country, strives to strengthen its resources, improve its systems, and innovate its services, to best suit its users.

Springer Nature

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[Foreword]

Chunli Bai

President of the Chinese Academy of Sciences

Nanoscience is the study of the interaction, composition, properties and manufacturing methods of materials at the nanoscale (from the micrometre scale down to the atomic scale). It encourages integration of many disciplines and fosters opportunities for scientific breakthroughs and innovations. In addition, nanoscience has a direct impact on our daily work and life by leading to discoveries of advanced technologies.

Nanoscience and technology started to attract public attention since the 1980s. In 2000, the United States took the lead to initiate the National Nanotechnology Initiative (NNI), which evoked a global boom of nano-related research. China too is committed to the development of nanoscience and technology, and has set up research plans keeping up with the international pace of progress. For instance, China established the National Steering Committee for Nanoscience and Technology in 2000 and founded the National Center for Nanoscience and Technology in 2003. The national medium and long-term development program includes nanoscience research plans. The National Natural Science Foundation of China and the Chinese Academy of Sciences have also funded a great deal of nano-related research. These initiatives have strongly encouraged the development of China's nanoscience and technology.

Springer Nature, the National Center for Nanoscience and Technology, and the National Science Library, Chinese Academy of Sciences collaboratively produced this whitepaper on China's development of nanoscience and technology. By looking at publications of high quality academic papers, patent applications, key areas of development, international collaborative networks and other aspects, it reveals recent trends of China's development in nanoscience and technology in comparison of the world. Having also incorporated experts' interpretations and views, the study applies both qualitative and quantitative analysis.

This whitepaper shows that over the past two decades, the development of nanoscience and technology has achieved great progress worldwide and made much positive impact on society. Meanwhile, it reveals the changes in related fields and the impact it has. The technical application of nanoscience and technology has influenced many fields such as materials and manufacturing, electronics and information technology, energy and environment, and medicine and health. The rapid development of nanotechnology brings new opportunities, as well as posing ethical and security challenges to the society. The potential risks should be evaluated and studied.

The analysis also demonstrates that China has become a strong contributor to nanoscience research in the world, and is a powerhouse of nanotechnology R&D. Some of China's basic research is leading the world. China's applied nanoscience research and the industrialization of nanotechnologies have also begun to take shape, with nano-related patent applications leading the world. These achievements are largely due to China's strong investment in nanoscience and technology. China's nanoscience research is also moving from quantitative increase to quality improvement and innovation, with greater emphasis on the applications of nanotechnologies.

There are challenges in the future of nanoscience and technology. We need to make true breakthroughs in basic research, close the gap between basic research and applications, and solve issues in energy, environment and health by applying nanotechnologies. Fostering young scientists with strong innovation abilities, as well as building value chains and a broader and more efficient international collaborative network are highly important. Through our effort, we expect to achieve more original breakthroughs in basic nanoscience research, apply nanotechnology to serve the country and benefit people, and contribute to making China a leading research powerhouse in the world. ■

FROM A SMALL SEED A MIGHTY TRUNK MAY GROW

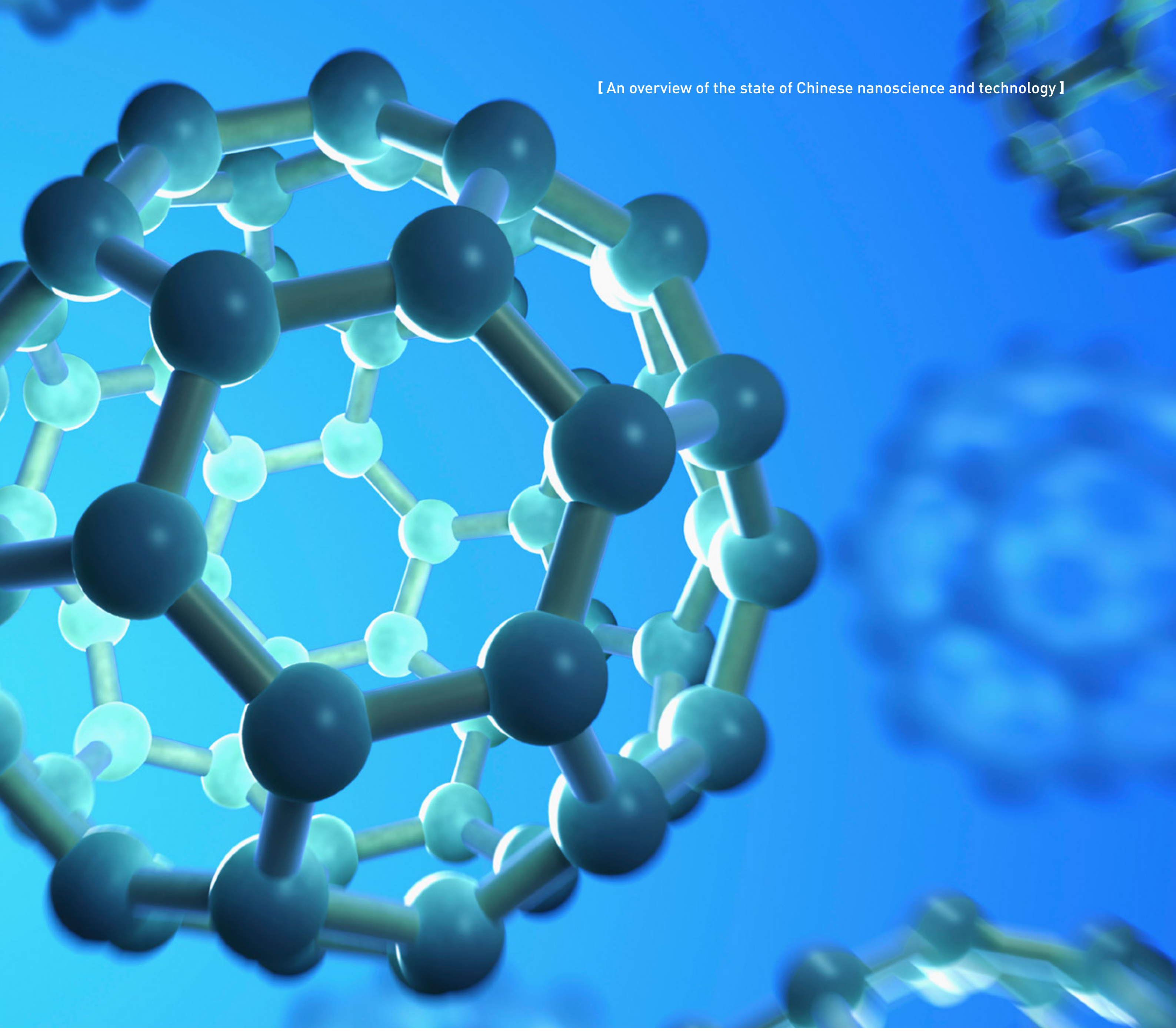
A quarter of a century ago, *Nature* convened a meeting in Tokyo that brought together the world's leading experts in a then emerging area of research that sought to understand and manipulate matter on the scale of atoms[1]. They called it 'nanotechnology', though not everyone was happy with the name. 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 although 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' 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 names.

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 the 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 a 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 of Education together established the National Center for 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 China to become the leading contributor to nanoscience and technology in the world today.

In this whitepaper, we have set out to give an overview of the state of

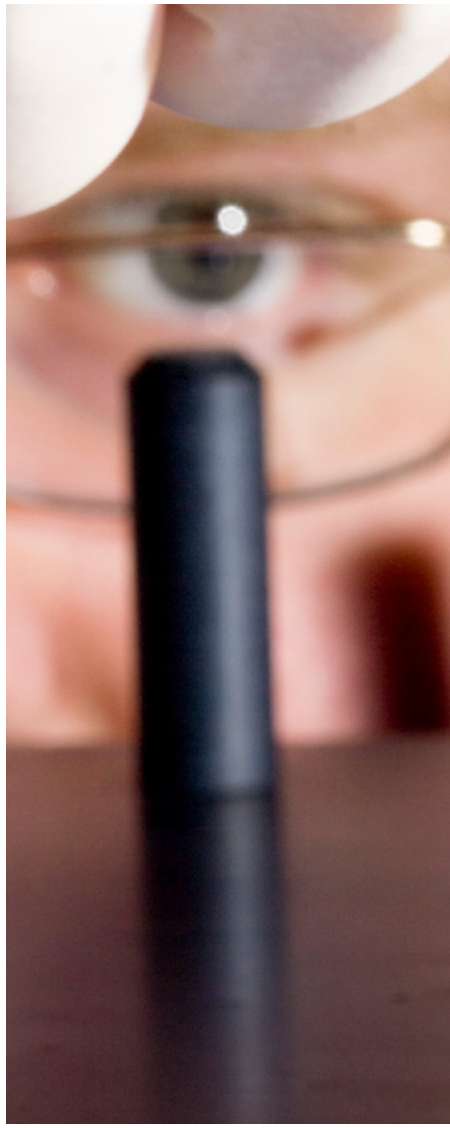


nanoscience and technology in China today. In the second section, we try to set the scene with a brief history of the discipline and the milestones that have marked that history to date. We describe some of the ways in which nanoscience is changing the materials that make up our world, how we communicate,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

In the third section, 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's strengths, weaknesses and areas of emergence in the field. And we will survey China patent output in related fields.

And in the fourth section, 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 makers might help to ensure the field continues to thrive. ■

1. Garwin, L. & Ball, P. Nanotechnology: Science at the atomic scale. Nature 355, 761–766 (1992); doi: 10.1038/355761a0



THE PAST, PRESENT AND FUTURE OF NANOSCIENCE AND TECHNOLOGY

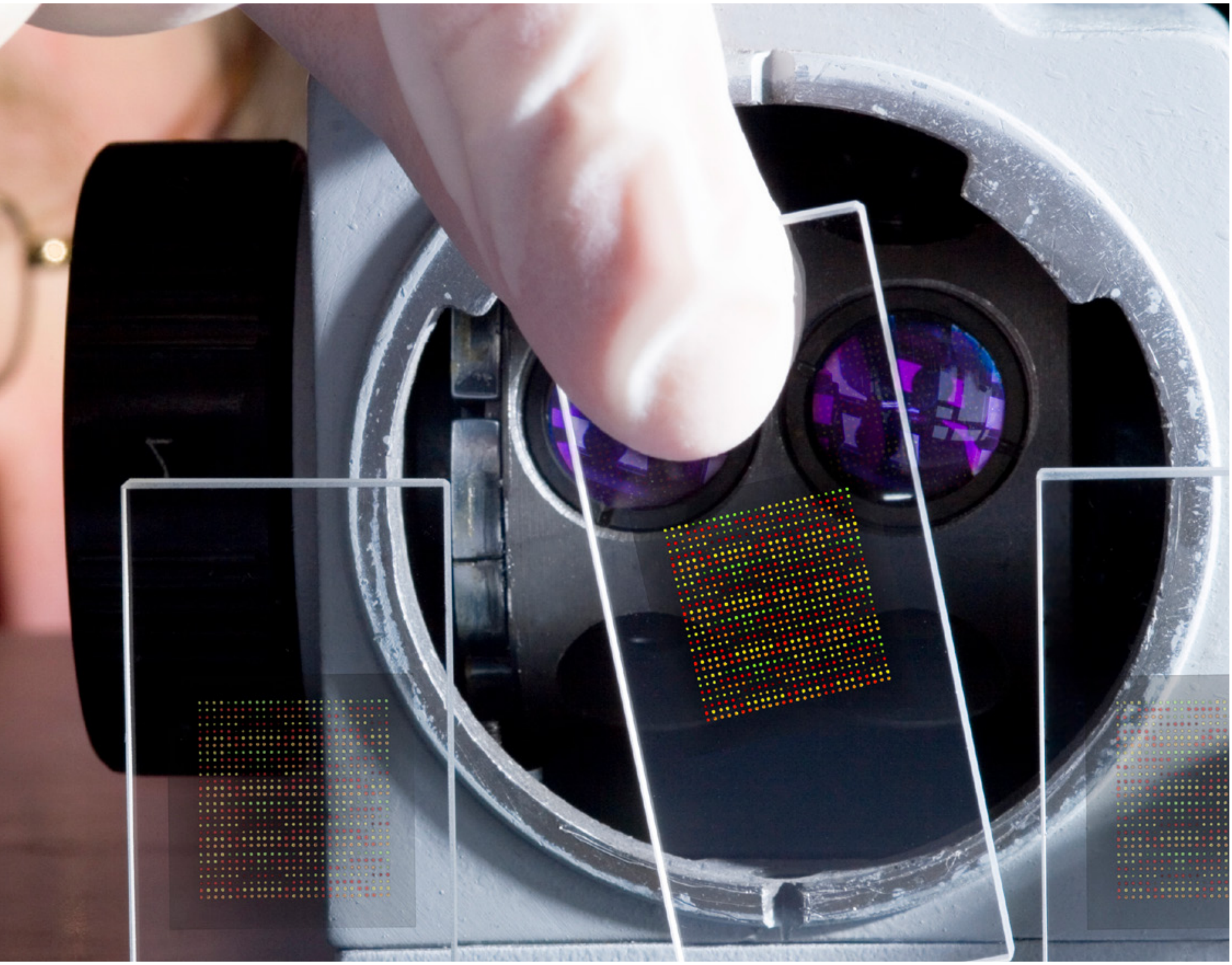
Nanoscience, in a nutshell, is the study of extremely small things on scales of between one and one hundred billionths of a metre — that is, 1-100 nanometres. At such small scales, the physical, chemical and biological properties of materials are very different to those at larger scales — often profoundly so. Alloys that are weak or brittle become strong and ductile, compounds that are chemically inert become powerful catalysts, semiconductors that are optically inactive become intense emitters of light. The ability to change the way matter behaves by manipulating it at the nanoscale has implications for most areas of science, technology and engineering and medicine.

Milestones in the development of nanotechnology

The development of nanoscience and technology as a distinct field of research is fairly recent. It has become a cliché to cite 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 Encyclopaedia 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 introduced 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 chemically-produced 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 such 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 buckminsterfullerene (C_{60}), a soccer ball-shaped molecule which is composed entirely of carbon and is extremely stable. This disproved the conventional wisdom at the time that there were only two stable allotropes of carbon — graphite and diamond — and ignited the imagination of chemists to the possibility of growing new and much larger classes of molecular structures than they had previously considered. In 1991, Sumio Iijima reported the growth of carbon nanotubes, which exhibit special electrical, thermal and mechanical properties, paving the way for wide applications of these tube-shaped nanostructures. Soon after, Charles Kresge and colleagues invented mesoporous molecular sieve nanomaterials MCM-41 and MCM-48, which are now widely used in oil refinement, water treatment, as well as drug delivery. In the latter half of the 1990s, groups led by Charles Lieber, Lars Samuelsson and Kenji Hiruma developed techniques for growing crystalline semiconductor nanowires — another vital step to bring nanoscience to the fields of photonics and optoelectronics. The isolation of individual sheets of graphene, a two-dimensional, one-atom-thick layer of carbon, achieved by Andre Geim and Konstantin Novoselov in 2004 has opened the doors to incredible future technologies. Being ultra-light, flexible and strong and highly conductive, graphene was hailed as a new wonder material.

The late 1990s and early 2000s saw growing applications of nanotechnology. One example is the invention of electronic ink in 1998, a paper-like display technology consisting of ink made of tiny capsules, which is now widely used in e-readers, such as Kindle. Another is the discovery of giant magnetoresistance in 1988 by Albert Fert and Peter Grünberg, which led to the development of magnetic read heads that enabled the drastic reduction in size and increase in capacity of computer hard disks. And the quantum dots discovered and developed by Ekimov, Efros, Brus (and many others) have made their way into a wide range of practical applications, including the light emitting elements of flat-screen televisions and as the fluorescent dyes for imaging the smallest structures in living cells and tissues.

Societal impacts of nanotechnology

The scale at which nanoscale materials are studied is small, but its potential impact on the way we live is large. Scientists and engineers around the world are making new discoveries about the microscopic world and translating their scientific discoveries to new products and technologies that reshape a wide range of industrial sectors, primarily materials and manufacturing, electronics and information technology, energy and environment, as well as medicine and health. With the sweeping societal impacts, the rapid development of nanotechnology has also brought ethical and safety issues that need to be addressed before we can enjoy the desirable fruits of nanotechnology.

Materials and manufacturing

The benefits of nanotechnology are primarily represented in new materials created by manipulating matter at atomic or molecular scales. With desired mechanical, chemical, electrical, thermal or optical properties, these new nanomaterials are applied in everyday commercial products, as well as industrial manufacturing.

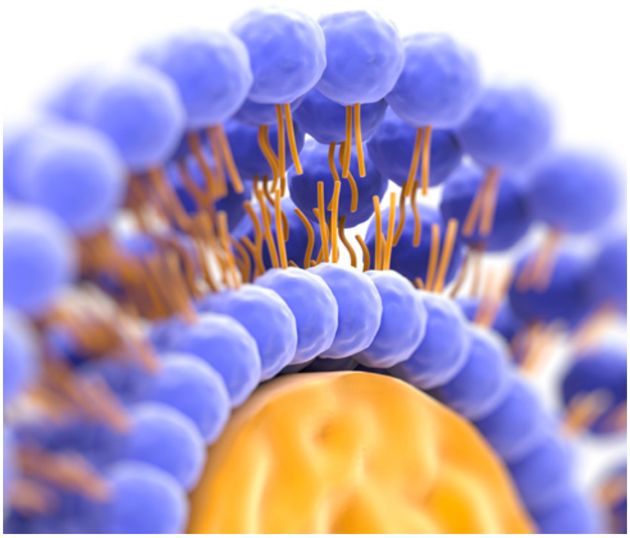
It is estimated that there are more than 1,600 nanotechnology-based consumer products on the market, according to a manufacturer-identified list prepared by the Project on Emerging Nanotechnologies , sponsored by the Wilson Center[2]. The most popular consumer use of nanomaterials is seen in health and fitness products, such as cosmetics, personal care products and clothes. An ordinary hair dryer or straightener may have used nanomaterials to be made lighter and more durable. Sunscreens have used nanoscale titanium dioxide or zinc oxide for sun protection, which appear to be invisible on the skin. Nano-engineered fabrics are used for wrinkle- and stain-resistant clothes, which are lightweight and may even prevent bacteria growth. Nanomaterials are also used in a variety of products, ranging from lightweight and stiff tennis rackets, bicycles and suitcases to automobile parts and rechargeable batteries.

In the manufacturing industry, nanostructured materials are used in coatings for machine parts and lubricants, reducing the wear and tear and helping to extend the lifetime of machines. Nanostructured alloys, with their great strength, high durability 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 catalysis 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 of a range of electronics, 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 an integrated chip would double every year (later revised to every two years), nanotechnology was still in its infancy. Thanks to the development of nanotechnology, integrated chips and transistors have become smaller and smaller as Moore predicted, while the computational speed is increasing, even though Moore's Law is stalling in recent years. In 2016, the world's first one-nanometre transistor was born. Made from carbon nanotubes and molybdenum disulphide, rather than silicon, the nanotube transistor demonstrated the potential to further shrink electronics, keeping 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. Devices using nano-scale semiconductor quantum dots, which are able to detect and generate single photons, are applied in cryptography systems, enhancing the performance and security of information networks. Another application of quantum dots, or inorganic semiconductor nanocrystals, is in the display industry. Nanotechnology has enabled ultra-high definition, energy-efficient, and even flexible displays for televisions, computers and mobile devices, which produce more vivid images. Using carbon nanotubes or silver nanowires, new transparent conductor materials are designed, opening the door to a variety of electronic devices with flexible touchscreens.

Energy and environment

By enhancing the development of alternative energy sources, making energy consumption more efficient and offering new solutions to environmental remediation, nanotechnology contributes to our environmental protection efforts. In the field of traditional energy sources, oil or gas extraction and fuel combustion are made more efficient with nanotechnology-based approaches or new catalysts. This has helped with reducing the pollution and energy use caused by power plants, vehicles, and other types of heavy equipment.

For many years, researchers have been working to improve the performance and cost-effectiveness of photovoltaic devices for converting sunlight to electricity by nanoscale engineering of 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 conducting polymers and metal-organic perovskites 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 have been developed, enhancing promises of alternative sources of renewable energy.

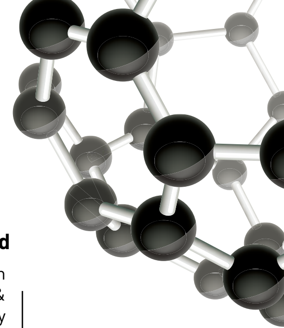
In energy storage, nanostructured electrode materials that support a wider range of electrochemical reactions could improve the capacity and performance of rechargeable batteries. Not only could this improve the storage capacity of future generations of batteries, it should reduce the weight and therefore improve 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 nanomaterials, such as molybdenum disulphide (MoS_2) membranes have assisted water desalination via more efficient filtering, while porous nanomaterials can work as sponges to absorb toxins from water, such as heavy metals or oil spills. Nanoparticles can also be used for cleaning pollutants in industrial water through chemical reactions. Moreover, nanofibers can trap small particles in the air and be used as air filters to clean up air.

Applications of nanotechnology in environmental remediation also lie in the detection of contaminants in air, water and soil. With unique chemical and physical properties, nanoparticles have higher sensitivity to chemical or biological agents and can be used as sensors to identify toxins in a simpler and faster way than conventional on-site tests and may even remove contaminants at the same time.

Medicine and health

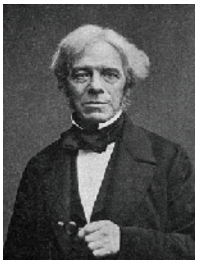
Arguably the most mature



[Scientific milestones]

1856: Observation of nanoparticles

Michael Faraday describes the wavelength-dependent scattering of light (Tyndall scattering) by chemically-produced gold colloids suspended in water.



1928: Near-field optical microscope

Edward Hutchinson Synge proposes the near-field scanning optical microscope to obtain images beyond the diffraction limit.

1931: Electron microscopy

Ernst Ruska and Max Knoll demonstrate the first electron microscope.

1935: Single molecule thin films

Irving Langmuir and Katharine Blodgett invent technique for growing monolayer-thick molecular thin films.

1946: Molecular self-assembly

Zisman, Bigelow and Pickett report the self-assembly of well-ordered molecular monolayers on a surface.

1959: Plenty of room at the bottom

Richard Feynman speculates on the potential of manipulating matter at the atomic level in his 'Plenty of room at the bottom' speech at a meeting of the American Physical Society at Caltech.

1968: Molecular beam epitaxy

John Arthur Jr and Albert Cho develop molecular beam epitaxy for growing high-quality single-crystal thin films.

1974: Nanotechnology coined

Norio Taniguchi coins the term 'nano-technology'.

1974: Surface-enhanced Raman spectroscopy

Martin Fleischmann, Patrick Hendra and James McQuillan report anomalous enhancement of Raman scattering, subsequently explained by Richard van Duyne and Alan Creighton to be due to field-enhancement by nanosized metal structures.

1974: Molecular electronics

Mark Ratner & Arieh Aviram propose the idea of a molecular diode.

1976: Atomic layer deposition

Tuomo Suntola invents atomic layer epitaxy thin film growth technique.

1980: Observation of naturally occurring quantum dots

Alexei Ekimov and Alexander Efros report existence and optical properties of nanocrystal quantum dots.

1981: Scanning tunneling microscopy

Gerd Binnig, Heinrich Rohrer invent the scanning tunneling microscope.

1982: DNA nanotechnology

Nadrian Seeman proposes the idea of DNA nanotechnology.

1983: Growth of semiconductor quantum dots

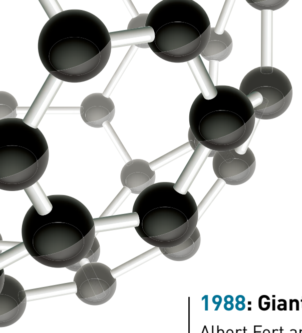
Louis Brus reports synthesis of colloidal semiconductor quantum dots.

1985: Buckyballs discovered

Harold Kroto, Sean O'Brien, Robert Curl & Richard Smalley discover C_{60} buckminsterfullerene molecule.

1986: Atomic force microscopy

Gerd Binnig, Calvin Quate and Christoph Gerber invent the atomic force microscope.

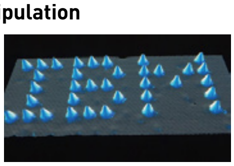


1988: Giant magnetoresistance

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

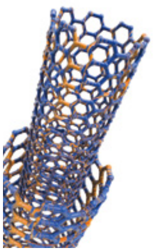
1990: Atom-by-atom manipulation

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'.



1991: Carbon nanotubes

Sumio Iijima reports growth of carbon nanotubes. A year later Millie Dresselhaus and colleagues propose a theory that accurately predicts the ratio of metallic to semiconducting nanotubes.

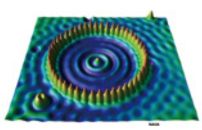


1992: Molecular sieves

Charles Kresge invents mesoporous molecular sieve materials MCM-41 and MCM-48.

1993: Quantum corrals

Michael Crommie, Christopher Lutz and Don Eigler report the confinement of electrons by quantum corrals formed by iron atoms on a copper surface.



1994: Stimulated-emission-depletion microscopy

Stefan Hell and Jan Wichmann describe a technique for optical imaging features below the diffraction limit by stimulated-emission-depletion fluorescence microscopy.

1994: Bistable molecular shuttle

Fraser Stoddart demonstrates a bistable chemically switchable molecular shuttle.

1994: Templated nanowires

Martin Moskovits grows aligned nanowire arrays using porous anodic aluminium oxide as a template.

1996: Nanopore gene sequencing

John Kasianowicz, Eric Brandin, Daniel Branton, and David Deamer demonstrate the ability to thread a single strand of DNA through a nanopore in a lipid bilayer membrane.

1997: Cs corrected scanning tunneling microscopy

Ondrej Krivanek demonstrates the ability to correct spherical aberration in a scanning tunneling electron microscope.

1998: Extraordinary optical transmission

Ebbesen, Lezec, Ghaemi, Thio, & Wolff report observation of extraordinary transmission of light through an array of subwavelength holes in a metal film.

1998: E-Ink

Comiskey, Albert, Yoshizawa & Jacobson report the invention of E-Ink.

1998: Crystalline nanowires

Charles Lieber, Lars Samuelsson and Kenji Hiruma independently develop techniques for growing of crystalline semiconductor nanowires.

1999: Molecular motors

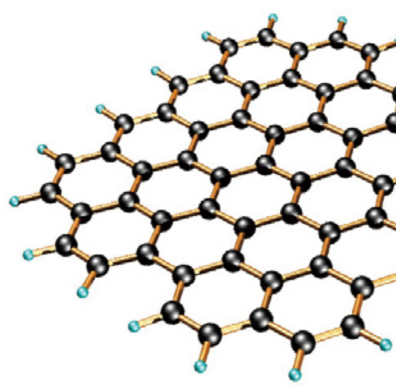
Ben Feringa and Ross Kelly report light-driven and chemically driven molecular motors respectively.

2001: Nanowire lasers

Peidong Yang demonstrates room temperature nanowire laser.

2004: Isolation of graphene

Andre Geim & Konstantin Novoselov describe a technique to isolate individual sheets of graphene.



2006: DNA origami

Paul Rothemund demonstrates a method for folding individual strands of DNA complex two-dimensional shapes.

2013: Artificial ribosomes

David Leigh creates a molecular machine that acts as an artificial ribosome to join together amino acids in a specific sequence.

form of nanotechnology is that realized by life itself. From the organelles of cells down to the operation of biomolecules such as 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 the electrical current that flows across 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, and increase 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. Nanostructured 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 cautions to the unintended environmental, health and social effects.

The biggest current concern is the health threats 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 a 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 responsible 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 U.S., 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 investigation 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 considerations of the potential risks, nanotechnology can be harnessed to change our lives and environment in a desirable way. ■

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2. See http://www.nanotechproject.org/cpi/

THE RISE AND RISE OF CHINESE NANOSCIENCE

It is no secret that over the past two decades, China's scientific output has grown at a rate that is unprecedented in recorded human history. In 1997, China-based researchers coauthored around 2 per cent of the scientific papers published globally by journals listed in the expanded Science Citation Index (SCI, compiled by Clarivate Analytics). China now contributes almost a quarter of all the primary research published in the world today. In few areas of research is this trend reflected more strongly than in nanoscience and technology.

To get a better understanding of the rise of Chinese nanoscience we looked at the China's research output relative to the rest of the world in terms of numbers of primary research papers, research contribution contained in Nature Research's recently launched Nano database, and finally patents.

Publication output for the past 20 years

To begin our survey of the state of nanoscience research in China, we obtained the numbers of papers published year-on-year by the world's leading countries in scientific research, filtered by nanoscience- and technology-related keywords, according to the extended SCI database. This included papers containing terms such as 'nanotube', 'quantum dot', and 'atomic force microscopy' (see Appendix 1 for a more detailed description of the methodology).

In 1997, around 13,000 nanoscience-related papers were published globally. By 2016, this number had risen to more than 154,000 nano-related research papers. This corresponds to a compound annual growth rate of 14% per annum, almost four times the growth in publications across all areas of research of 3.7%. Over the same period of time, the nano-related output from China grew from 820 papers in 1997 to over 52,000 papers in 2016, a compound annual growth rate of 24% **(Figure 1)**.

Unsurprisingly, the relative contribution of nanoscience research as a fraction of the total scientific output has also grown considerably **(Figure 2)**. Twenty years ago only around one-in-fifty papers published in the world involved research related to nanoscience or technology. Today, that has increased to over one-in-ten. Throughout that time, nanoscience has made a more

FIGURE 1 | GROWTH OF NANOSCIENCE.
The total output of papers related to nanoscience and technology published in journals listed in the SCI has been growing for the past two decades.

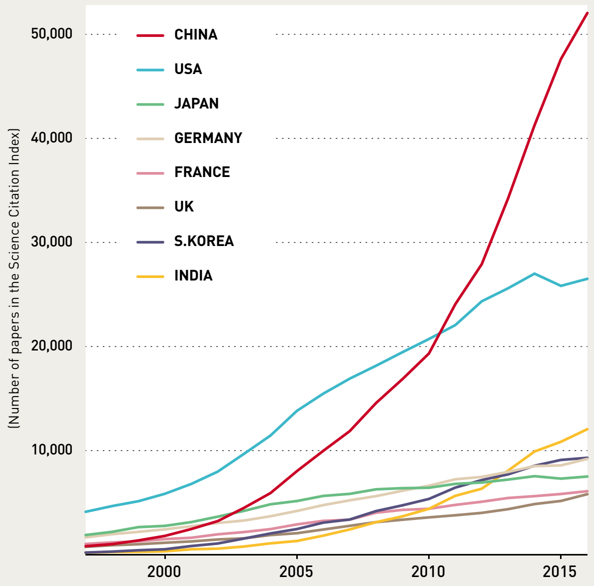


FIGURE 2 | CONTRIBUTION OF NANOSCIENCE TO TOTAL SCIENTIFIC OUTPUT.
Papers related to nanoscience and technology represents an ever growing fraction of the total scientific output of most countries. For China, South Korea and India, that fraction is now well above the global average.

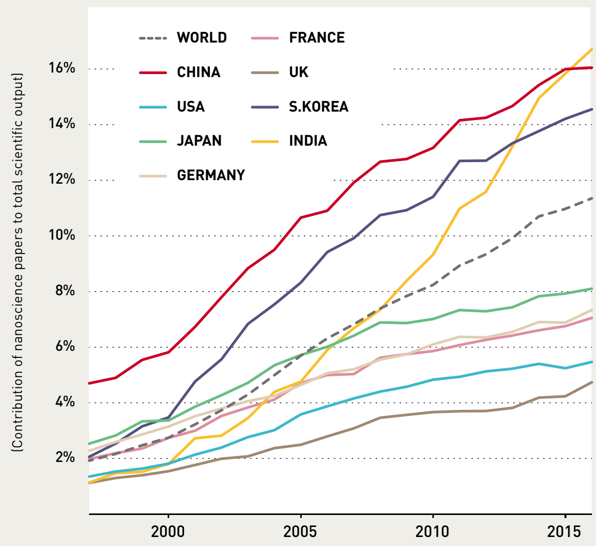


FIGURE 3 | GROWTH OF CHINESE NANOSCIENCE.
As a fraction of the global output of nanoscience papers published in journals in the SCI, the contribution from researchers based in China has been growing steadily for decades.

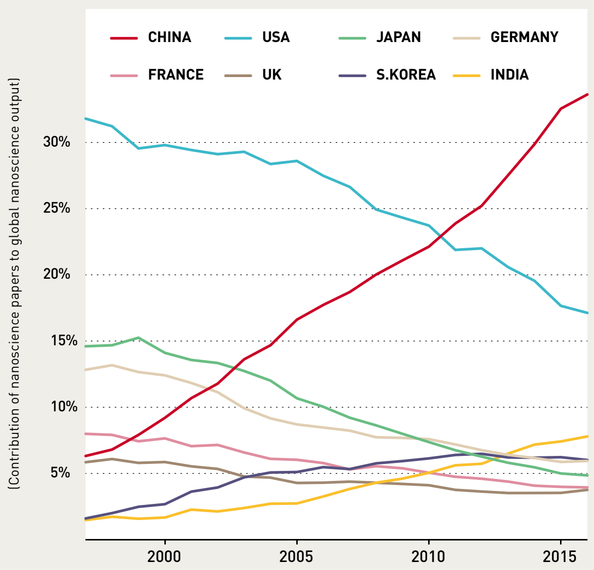
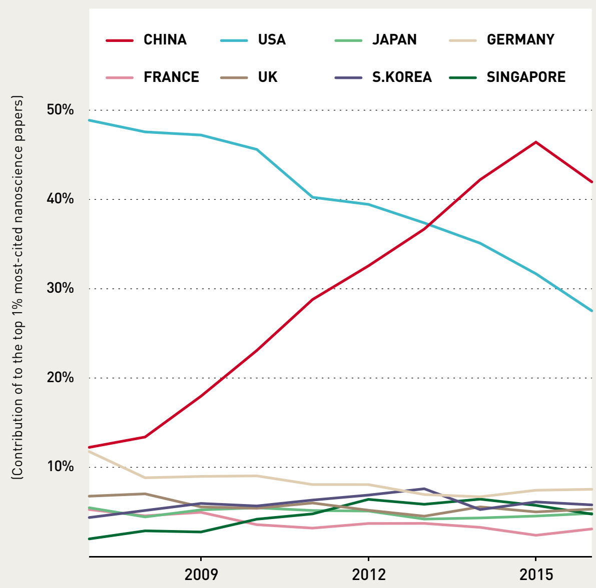


FIGURE 4 | GROWTH OF HIGH-IMPACT NANOSCIENCE.
China is now the largest contributor to the top 1% most-cited papers related to nanoscience and technology.



significant contribution than the global average to the research output of just two countries — China and South Korea. These have now been joined by India, as countries for which the nanoscience contribution to their total output is around twice that of all other leading countries in the field.

The growth of Chinese nanoscience is even more impressive when viewed as a fraction of the global output **(Figure 3)**. China's contribution to global total has been growing steadily. In 1997, Chinese researchers co-authored just 6% of the nano-related papers contained in the SCI. By 2010, this grew to match the output of the USA. They now contribute over a third of the world's total nanoscience output — almost twice that of the USA. Against this backdrop of the rapid rise of China, only South Korea and India have seen growth in their contribution, with most other countries either seeing a gradual decline or levelling off in their relative nanoscience output. It must be stressed, though, although the relative contribution of these countries may be falling, the total output of most continues to rise **(Figure 1)**.

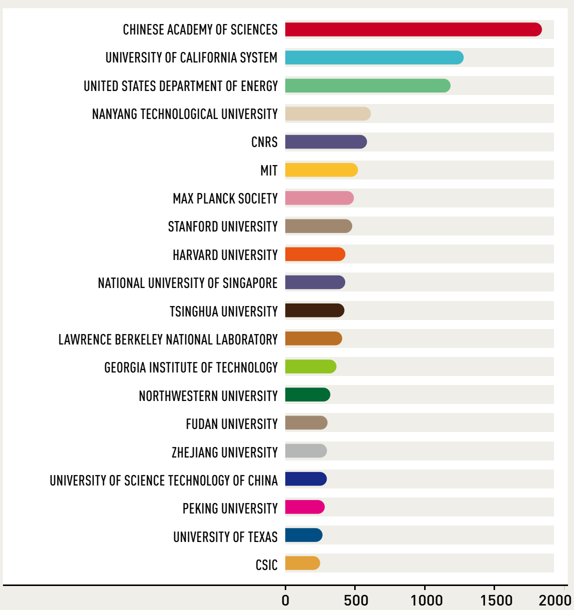
Rise of high-impact research in China

When it comes to measuring the impact of any given contribution to scientific research, it is important to note that sheer quantity is not the same as quality. What's more, although measuring the quantity of a country or institution's output is relatively straightforward, determining the quality of that output is more challenging. There is no universally accepted metric for assessing research quality. But one way of measuring the impact that a piece of research has had is the number of times that it has been cited. And so, to this end we have analysed the top 1% most-cited papers in the field of nanoscience and technology in the SCI **(Figure 4)**.

Here we find that not only is the precipitous growth of Chinese nanoscience in terms of the total volume matched by a similar increase in its contribution to the most-cited papers, it is exceeded by it. Since 2007, 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.

FIGURE 5 | LEADING INSTITUTIONS IN HIGH-IMPACT NANOSCIENCE.

Institutions with greatest contributions to papers in the top 1% most-cited nanoscience papers of the past decade



Chinese institutions lead the world

Much of the progress in China's rise to become the world's leader in nanoscience has been driven by CAS. Ten years ago, CAS's contribution to the top-cited research was already impressive, ranking third in the world behind the University of California System 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)**.

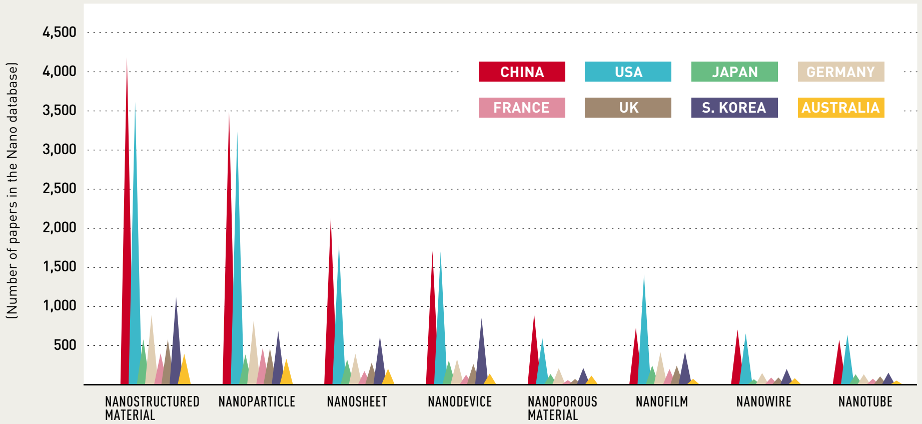
The rapid growth of nanoscience in China has a lot to do with its consistent and strong financial support for research in the field. As early as 1990, the State Science and Technology Committee, the predecessor of the Ministry of Science and Technology (MOST), launched the Climbing Up project on nanomaterial science. Nearly a decade later, MOST funded a national Nanomaterial and Nanostructure 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[3]. 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[4].

With the robust government funding support, a growing number of Chinese scientists have been attracted to nanomaterials research. The brain boomerang, 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.

Insights from the Nano database

To get a more detailed picture of the particular strengths and focus of 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

FIGURE 6 | HOT NANOMATERIALS.
The number of papers in each of the eight most commonly researched nanomaterial types in the Nano database suggests that China's output is strong in most.



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 enlisting 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, nanosheets, nanodevices and nanoporous materials. This is similar to the most popular nanotypes observed in other research powerhouses **(see Figure 6)**. It is worth noting that China has relatively higher research intensity on nanoporous materials and its papers on nanodevice have seen a soar in the past three years.

For newly emerging nanostructures, defined as nanostructures not in the top 10 most studied, but which have seen much larger increases in research output from 2014 to 2016 compared to other nanotypes, supramolecular chemistry is the most commonly studied among the eight big research countries analysed here. In addition, other nanostructures into the use of which research is rapidly increasing in China also include fullerenes, DNA origami and nanogels. While in other countries, like the United States, Germany, South Korea and Japan, it is research into nanocapsules that is growing faster.

Differing applications of research

Studies of nanostructures typically can lead to development of functional materials. Research papers in the Nano database reporting various nanomaterials usually have also discussed possible applications. Of the eight big research countries investigated, catalysis, electronics, medicine- and energy-related applications are the most commonly explored, but there are variations across countries. For instance, China is the strongest contributor to papers in catalysis research, while the United States leads in nanomaterials for electronics **(see Figure 7)**.

China has a clear leading edge in catalysis research, which is the most popular area of the country's quality nanoscience papers. The strength in catalysis research has its tradition in China, possibly driven by the needs for the development of 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 the output and impact of China's life science research typically lags behind that of the United States and Europe. This suggests that nanomedicine is an area in which China could leverage its strengths in chemistry and material science to carve out a significant niche in the life sciences.

Energy-related applications, specifically, energy storage and power generation is another frequently studied nanoscience area in China. The area also sees the fastest growth in the past three years among China's top 10 popular application areas of nanomaterials. With mounting public pressure to tackle the deteriorating environmental problems, China is putting great effort into the research and development of new energy, as well as technologies enabling efficient energy use and environmental remediation. The potential exhibited by nanomaterials has made energy nanotechnology a promising area, attracting many Chinese researchers, who are leading in nanostructures and nanomaterials for batteries and energy storage and conversion.

China is relatively weaker in nanomaterials for electronics applications, compared to other research powerhouses. But robotics and lasers are emerging applications areas of nanoscience in China, defined as those not among the top 10 applications but show rapid increase in research output in the recent three years. Moreover, nanoscience papers addressing photonics and data storage applications also show strong growth in China.

Applied versus fundamental research

Nanoscience and nanotechnology, with its broad range of potential applications and societal impact, is highly applied in nature. As a result, nanotechnology-inspired patent applications are large in quantity and are increasing steadily. But at the global scale, the growth in patent applications is not as fast as that of the SCI research papers. When comparing number of nano-related patent applications against that of research publications, different countries present different strengths.

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 a 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 8)**. Only South Korea and Australia exhibited a similar trend.

The guidance of the governmental 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. 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 element in scientific research. For

FIGURE 7 | HOT APPLICATIONS.
China's output is strongest in the majority of the most frequently-cited application areas listed in the Nano database, with the exception of electronics, optoelectronics, and power generation, in which the USA is in the lead.

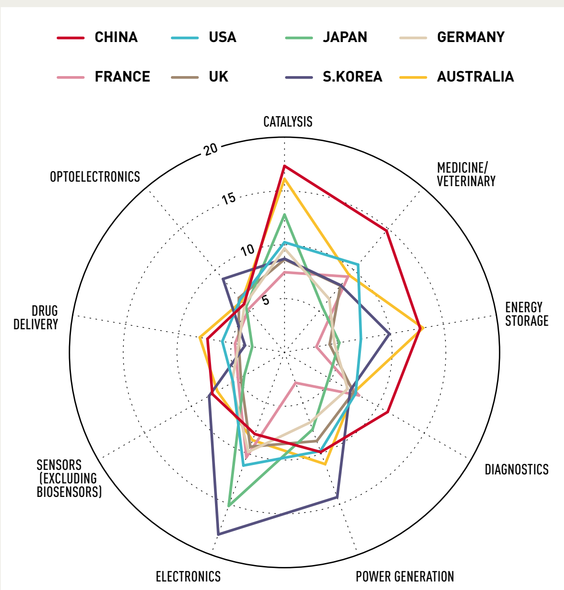


FIGURE 8 | APPLIED VERSUS PURE RESEARCH.
Among papers included in the Nano database in the years 2014–2016 those from China were the most likely to cite a specific application of the research.

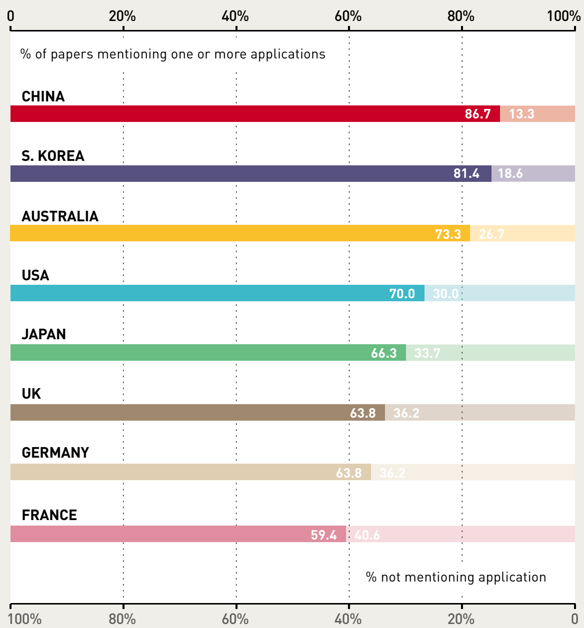
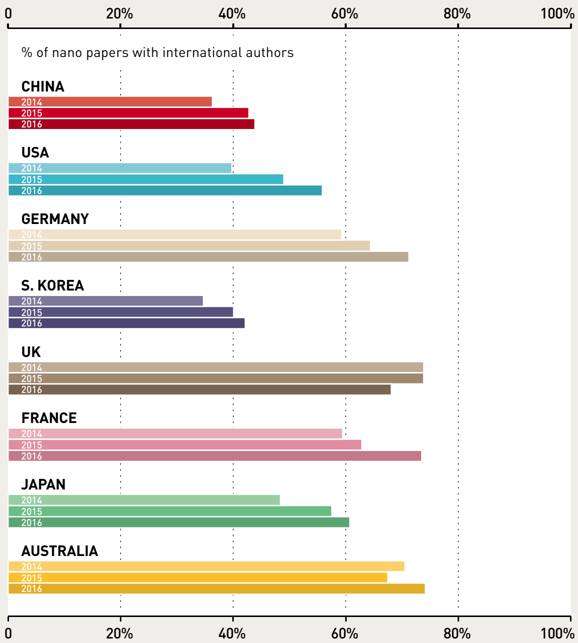


FIGURE 9 | ROLE OF COLLABORATIONS.
Level of international collaboration for papers in the Nano database.



nanoscience, a highly interdisciplinary field, collaboration is even broader. Nano-related research output generally presents a higher level of international collaboration compared with total research output in the SCI.

With great emphasis on international collaboration, the number of Chinese papers with international coauthors has been increasing. According to data from the SCI, the proportion of Chinese total research output with international collaboration has increased since 2010 and reached 24% in 2016[5]. Looking at quality nanomaterial-containing articles in the Nano database, the percentage of internationally collaborated papers increased from 36% in 2014 to 44% in 2016 for China **(see Figure 9)**. However, China's level of international collaboration, similar to that of South Korea, is still much lower than that of the western countries and the rate of growth is also not as fast as those in the United States, France and Germany.

The United States is China's biggest international collaborator, contributing to 55% of China's internationally collaborated papers on nanoscience that are included in the top 30 journals in the Nano database. It has collaborated with China on 2,123 papers published 2014 to 2016, accounting for 21% of the total number of quality nanoscience papers published by US authors. Germany, Australia and Japan follow in a descending order as China's collaborators on nano-related quality papers. Particularly, China is an important collaborator for Australia, contributing to about one third of Australia's research output in top 30 nanoscience journal titles.

China's patent output

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[6]. The number of patents in China has been rising 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 accumulative total in the last 20 years, accounting for 45% of the global total. China's accumulative total number

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

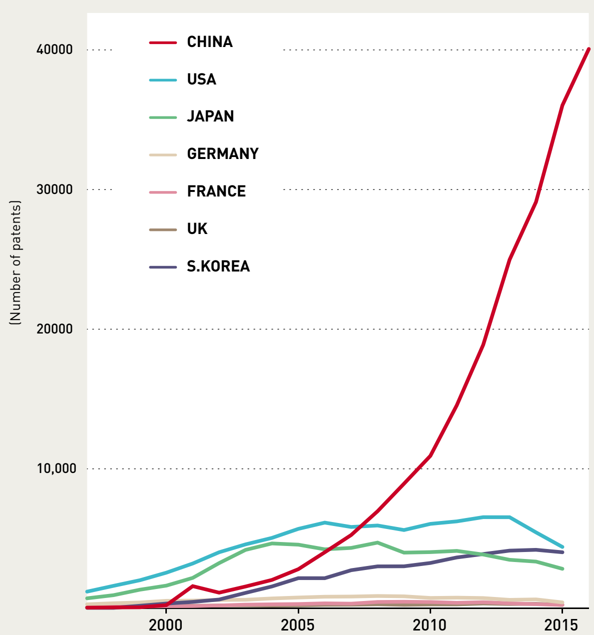
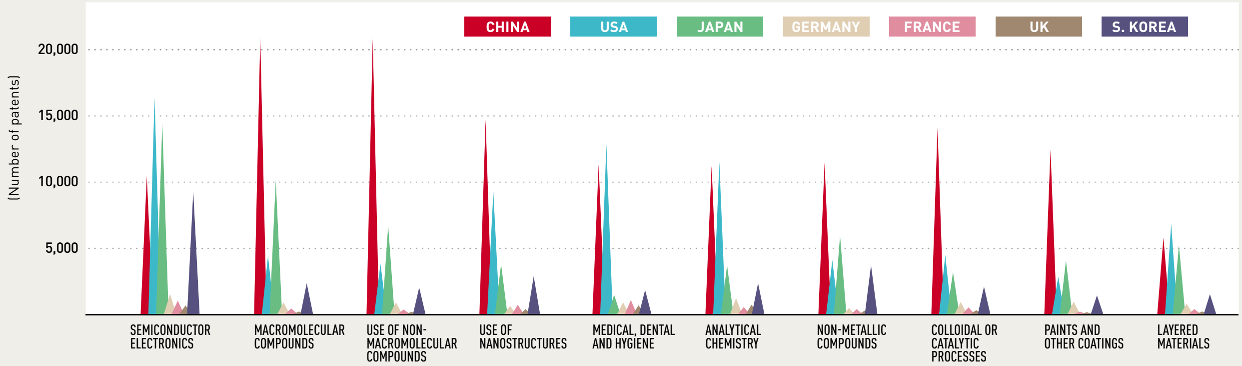


FIGURE 11 | PATENT OUTPUT BY INDUSTRIAL APPLICATION.

Total output from 1997–2016 in areas related to nanoscience and technology by Cooperative Patent Classification subclass.



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 accumulatively, whereas the proportion in the United States is nearly 50%. And in some European countries, like the UK and France, more than 70% of patent applications are filed overseas.

Five Chinese institutions, including the CAS, Zhejiang University, Tsinghua University, Hon Hai Precision Industry Co., Ltd. and Tianjin University have emerged among the global top 10 institutional contributors to nano-related patent applications. CAS has ranked 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.

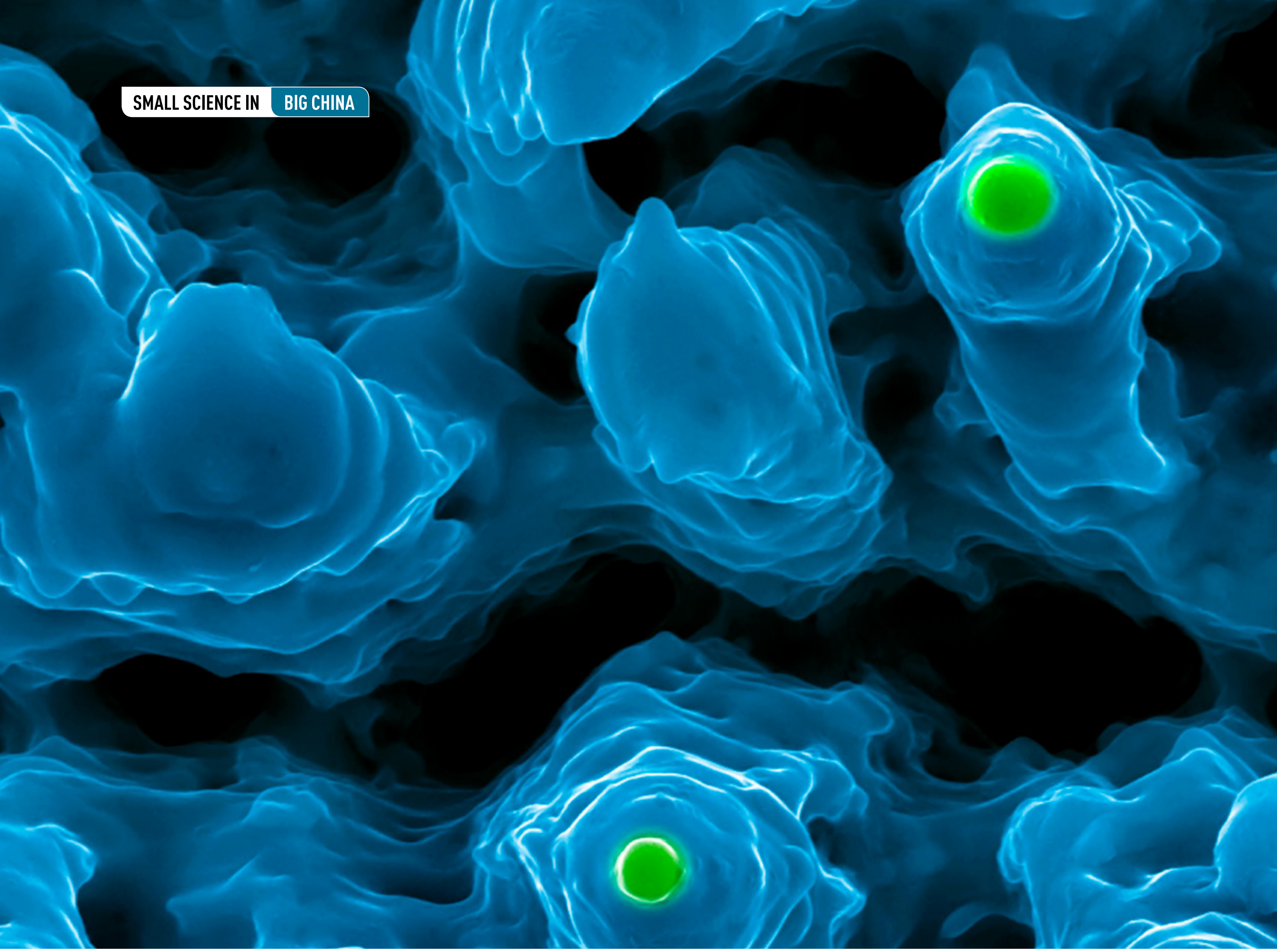
Range of applications of China's nano-related patents

Globally, nano-related patent applications are primarily concentrated in the areas of electricity and electronics, chemistry and metallurgy, medicine and health, superfine techniques and materials. Patents for medical, dental, or hygiene related devices or technologies, polymer materials, as well as catalysis and colloid chemistry-related patents have been increasing consistently over the past 20 years; while those for semiconductor devices, the most common category for nano-related patents, are declining since after 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 macromolecular compounds. In comparison, nano-related patent applications in the United States, South Korea and Japan are mainly for electronics or semiconductor devices, 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 macromolecular compounds are also the fastest growing areas. These may include paints, inks, dyes, adhesives and textile treating techniques or fibres. Patents for technologies or apparatus enabling chemical or physical processes, such as catalysis are also increasing fast in China. ■

3. See Bai, Chunli. Ascent of Nanoscience in China Science 2005, 309, 61–63
4. See Weiss, P. S. A Conversation with Dr. Chunli Bai: Champion of Chinese Nanoscience ACS Nano 2008, 2(7), 1336–1340
5. See Nature Index-China 2017 http://www.nature.com/nature/journal/v545/n7655_supp/full/545S39a.html
6. Data after 2014 are incomplete due to the requirement for confidential period associated with patents.



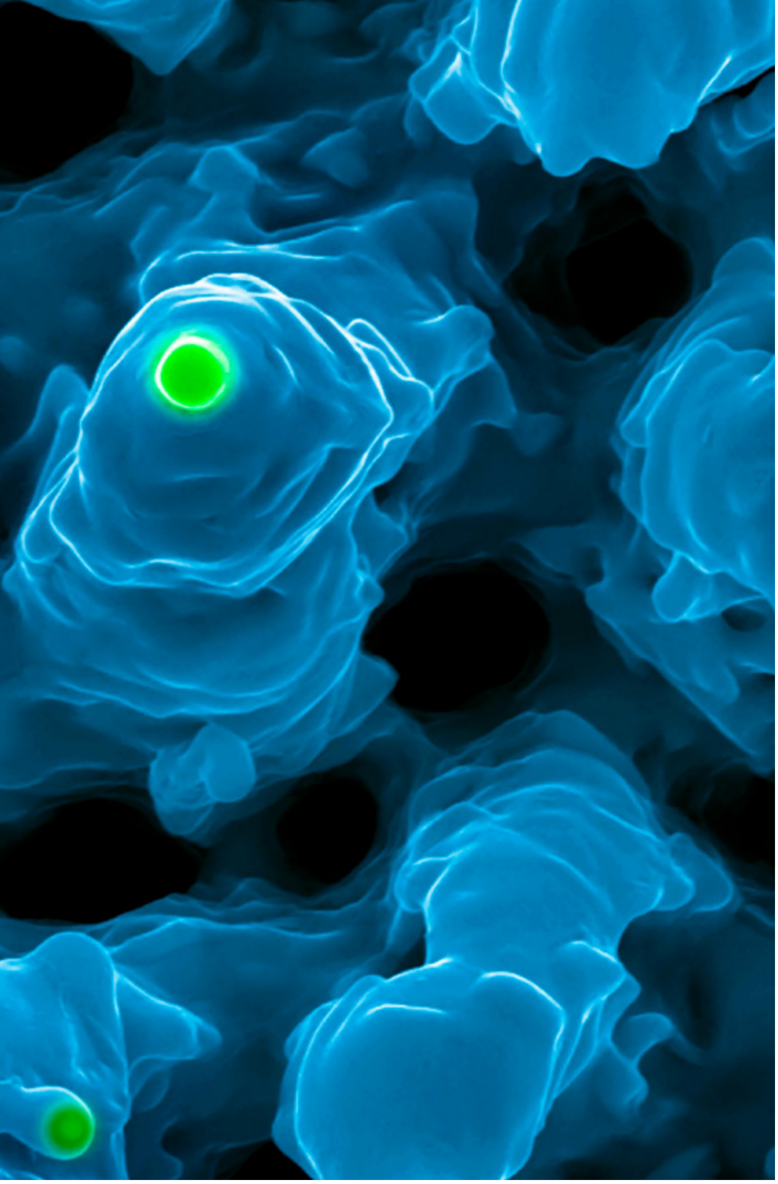
EXPERT VIEWS ON THE OUTLOOK FOR CHINESE NANOSCIENCE

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 opportunities there are also challenges. To better understand both, we conducted interviews with a range of experts from the Chinese nanoscience community.

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, nanostructure-based catalysts have wide applications in the chemical or chemical engineering industries, as well as the oil refining industry. For instance, Chinese scientists recently developed a catalyst that enables the direct conversion of synthetic fuel gas to light olefins, the basic building blocks of plastics — a process that is already being considered for industrial applications. The growing needs of industry continue to drive development of nanocatalysists and China is expected to maintain its competitive edge.

Yet, interviewed experts recognize that more precise control of nanostructures remains a challenge, which is required to produce catalysts with high efficiency, activity and selectivity, as well as long lifetime. Some point out that synthesizing a new catalyst and getting the research published are 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 are widely recognized, particularly in China, where rising environmental problems have caused serious attention from the government. The Chinese government's dedication to long-term investment into new energy study brings bright prospects for the development of nano energy 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

> **"If there is one change that I want to see most, that would be greater investment into the R&D of nanotechnology."**

foldable graphene oxide film-based device that produces desalinated 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.

in medical devices and medical imaging is also an area that held high prospects by interviewed scientists. "The integration of nanomaterials in electronic devices or wearable devices for medical use will make highly desirable products," said an expert in the field.

However, China is relatively weaker in basic

> **"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 new promising field. "The exciting thing for nanomedicine is its diagnostic and therapeutic features," said an expert in the field. "By using nanotechnology, we can control drug release and have 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

life science research and biomedical R&D compared with some advanced western countries. This has limited the development of nanomedicine, given the lack of expertise in biomedicine. Scientists currently conducting nanomedicine research are primarily with chemistry or material science backgrounds, who have limited experience in animal models and clinical studies. "The lack of expertise in biological and medical sciences is one of the biggest challenges for my research," said an expert in nanomedicine. The Chinese government has put great stock in the development of life sciences and biomedicine and quality research outputs in the area are rapidly growing.

Challenges

Boosting research impact

The Chinese government's significant investment in nanoscience and technology is aimed at developing technologies that can be industrialized to boost economic growth. However, despite the high numbers of academic paper publications and patent applications, the industrial impact of China's nanotechnology is still limited. There is still a gap between nanoscience research and the industrialization of nanotechnologies.

Most of the interviewed 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 R&D work that is aimed at commercialization of products. Such applied research can be more costly than basic nanoscience research and industrialization of a product or technology, or scaling up the production may cost billions of RMB, according to some researchers. "The enterprises, which have an edge on product R&D work and commercialization, need to be involved," said another researcher. "As a key player in nanotechnology development and its application, they need to be encouraged to invest more in R&D."

"To me, basic research is to generate new knowledge, concepts or theories, while applied research is geared towards applications and new products that make an impact. But now many people are doing something in between and there is lots of repeated research; many people are just following suit. I personally think we need [to focus] more on applications."

Currently, the industry is involved to some degree. Many nanoscience researchers collaborate with enterprises frequently and a growing number of enterprises are willing to work with scientists at universities or research institutes by funding their research and developing new technologies or products with them. Some also invest heavily in 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 relatively low 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 to really mobilize enterprises to invest into R&D, established systems are needed that bridge dialogues between the scientific community and the industry, streamline the processes of research translation and industrialization, and keep the investment channels open.

"If there is one change that I want to see most, that would be greater investment into the R&D of nanotechnology."

How to enhance the application of nanoscience research is identified as one of the biggest challenges for China's nanoscience 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. Therefore, keeping a balance between fundamental and applied research is essential when highlighting science and technology innovation with an emphasis on research application.

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.

"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."

Statistics suggests that in general, only a small proportion of China's total research expenditure is spent on basic research, compared with most western countries. This seems to be contradictory to the perceptions of most nanoscience researchers interviewed for this paper. Different definitions of applied versus basic research play a role here. As in a survey conducted by Nature Research two years ago suggested, nanoscience and nanotechnology are considered applied research by scientists included in that study, while basic research refers to fundamental studies of life sciences, physical sciences or geosciences that have no clear signs of immediate application. While the applied research referred to by most nanoscience researchers in this study is actually translational research, transforming lab results to products on the market. Yet, as some researchers suggest, perhaps commercial companies should take a leading role in closing this gap in commercialization is, while "the remit of professors should still be focusing on scientific studies." Or, probably as a researcher commented, "as long as you do something good [do good research], it doesn't matter whether it's basic or applied research."

In this sense, allowing the room for scientists to freely explore their creative ideas, following their intrinsic interest in science is the key. Too much emphasis on the sheer numbers of journal publications or patent applications can skew the purpose of research from the discovery of new knowledge to merely a means to generate papers and patents.

"It is important to enhance the application of research, but when the quantitative measures of application are too much emphasized in the research evaluation, the

> **"It is important to enhance the application of research, but when the quantitative measures of application are too much emphasized in the research evaluation, the practical value of a patent application tends to be reduced."**

practical value of a patent application tends to be reduced."

"Research is like a Gaussian curve — there are very few really bad research and only a few of highly impactful research. Just using citations may not be a good way to judge the importance of research."

Encouraging collaboration

With the growing number of foreign-trained Chinese scientists returning from abroad and the strong government support in this effort, interviewed nanoscience experts are confident that internationally collaborative research will grow in China and that the network of international collaborators will expand. Several younger researchers explained that they collaborate frequently with their former coworkers, supervisors or colleagues based overseas as they have already established close ties with them.

Different from more than a decade ago when international collaborations in China was primarily driven by the needs to learn foreign expertise or advanced skills, it is now more out of the need to find complementary expertise and skillsets. "Researchers from different countries have different backgrounds and their own niche areas," said a nanoscience expert. "For instance, we recently collaborated with Japan on a gene expression intervention project for the treatment of pancreatic cancer. We are good at preparing the nanomaterials, while the Japanese researchers have strong medical backgrounds and are highly experienced with animal models. We can complement each other."

Moreover, China is taking a greater leadership role in more and more international collaborative projects, as China has built up its expertise in certain areas of nanoscience. "We are already leading in energy conversion and storage research and play a predominant role in several collaborative projects on new energy batteries," said one researcher specializing in nano energy.

As one senior researcher commented, program-driven collaboration needs to be further encouraged so that research can be made more efficient by pooling complementary expertise. And while personal relationship plays a significant role in collaboration, "fostering a culture of collaboration is important to make collaborative research really sustainable." He suggested that change is slowly emerging with the recognition of the need to improve the research evaluation system.

Enhancing collaboration between the disciplines

As has already been noted, nanoscience is inherently interdisciplinary, spanning as it does many different traditional disciplines including chemistry, physics, engineering, biology and medicine. Progress in the development of everything from the next generation of computer chips to the future of cancer treatment relies on our understanding of how the world works at the nanoscale. And yet, even researchers from neighbouring disciplines such as physics and chemistry often use very different language to describe the world they see. Breaking down the boundaries between traditional disciplines and fostering truly interdisciplinary approaches to understanding are crucial to improving progress in nanoscience and technology.

"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."

Following the global trend, many Chinese universities and research institutes are emphasizing interdisciplinary research these days. However, China is still relatively weaker in interdisciplinary research, as one researcher points out. "Most funding organizations, such as NSFC, categorize their funding programs by traditional academic subjects, which is not supportive to the development of interdisciplinary fields, such as nanoscience," he said.

The categorization of funding programs by conventional disciplines does not bother most interviewed researchers much, as most nanoscience researchers are chemists and can simply apply for funding in the chemist category. Also, the NSFC does have some special programs focused on nanoscience, and so does MOST. However, some did note that the limited scope of cross-disciplinary integration may hamper diversified growth of nanoscience. Most of times, the collaboration is within material scientists or chemists themselves, though with different

> **"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."**

sub-area expertise. A mechanism that encourages greater cross-disciplinary collaboration between chemists and life scientists, environmental scientists or even geoscientists, for instance, is lacking.

"Currently, interdisciplinary collaboration on nanoscience is still too narrow. Say, the majority of people [doing nanoscience] are from chemistry or material science backgrounds, while [there are] not many coming from physics or medicine backgrounds. In this sense, true cross-field exchange is still not enough… We may need more forums for such cross-disciplinary exchange, and need to learn each other's languages for a dialogue of mutual understanding."

Fostering the young

A common theme we encountered in our interviews with experts in the field is the expectation that the greatest source of the ideas and inspiration that will drive innovation in nanoscience (and indeed all of the sciences) is the next generation of researchers. Taking advantage of this precious resource isn't just about ensuring that China's young researchers have sufficient funds to carry out their research, but that they are supported in their career development and, perhaps most importantly, that they are able to find their own voices and that those voices are heard.

The Chinese government has already offered generous support to young scientists, with the launch of several high-profile funding programs targeting the young. Examples are the NSFC's National Science Fund for Distinguished Young Scholars, the Thousand Young Talents Program initiated by the Organization Department of the Central Committee of the Communist Party of China, as well as the One Hundred Talents Program of the CAS. Not confined to any specific subject areas, these programs allow winning young scientists some freedom to explore their interested fields. Several interviewed nanoscience experts who are based in the United States acclaimed that the funding support received from the government by Chinese young scientists in nanoscience exceeds the funding received by their peers in the United States or other advanced countries.

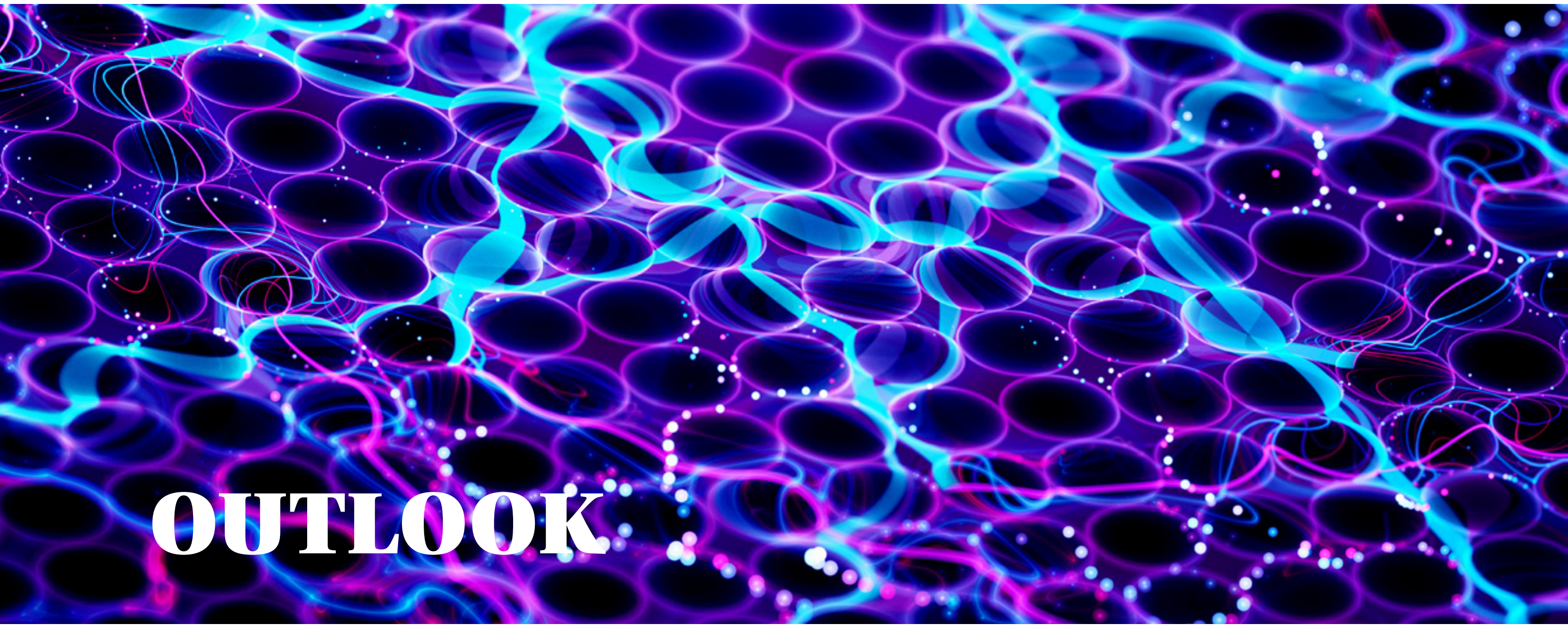
But the competition for research funding is becoming more intense, as more and more young scientists enter the field or return from abroad. While too much competition may hamper innovation, most interviewed young scientists generally do not worry that much about the increasing competition for funding, rather, they emphasize that the soft environment is more important. They expect establishing channels that allow the suggestions or creative ideas of the young to be heard.

"In Chinese scientific community, the new supersedes the old at a relatively slower rate than in the United States and some other advanced countries. We need more effort to promote the advancement of the field … This is not just about support in the facilities or funding, the soft environment is essential. To encourage the sprouting of fresh ideas, young scientists need to be given more say."

Also, many of the current funding programs for the young are based on proven track records of established achievements. The current evaluation system is also geared towards past achievements or inclined towards overseas experience. Some talented young researchers may never be able to obtain the resources needed to explore their ambitions. How to select promising researchers before they have made their discoveries remains an issue and an improved talent selection mechanism is needed.

Fostering talent starts from improving educational programs. For the development of nanoscience, making it sustainable as a subject of science, enhancing interdisciplinary collaboration, and improving the quality of research all require targeted educational programs on nanoscience. Over the past few decades, with the rapid development of nanotechnology, quite a few world-renowned universities have established academic programs on nanoscience and nanotechnology for training master's or PhD students in the area. In 2010, China's Soochow University partnered with the Suzhou Industrial Park and the University of Waterloo in Canada to establish the College of Nano Science and Technology, the first of its kind in China. Aimed at cultivating talent with expertise in nanoscience, the college pioneers coherent training programs on nanoscience for undergraduate, Master's and PhD students. It attempts to integrate student training, scientific research and application of nanoscience and technology and represents China's first stab at an interdisciplinary nanoscience educational program.

To address the growing needs for talent with nanoscience expertise, CAS has also decided to establish a nanoscience and technology college at the University of Chinese Academy of Sciences. Led by the NCNST, the new college will be dedicated to integrating nanoscience research with undergraduate and graduate education, aiming to become a world-class educational base for multidisciplinary talent with expertise in nanoscience and technology. The development of various industries, such as biomedicine, energy and information technology also requires multidisciplinary talent with nano knowledge, said the NCNST director. A nanoscience college also helps with establishing a new knowledge framework that integrates multiple subject areas to enable better understanding of nanoscience and make it an interdisciplinary new subject in our academic systems. ■



OUTLOOK

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 a reality did not believe those tools would lead to commercial nanotechnologies any time soon. Today machines that sequence genomes by threading individual strands of DNA through nanometre-wide holes, sunscreens that use ceramic nanoparticles to block harmful ultraviolet rays, and computer chips built from transistors with features just 10 nanometres wide are commonplace.

The remarkable pace at which nanoscience and technology has developed is matched only by China's own scientific and technological development. China is now the world's leading contributor to nano-related research in terms of both its total and high-impact publication output, by a substantial margin. It has reached this level largely by building on its traditional strengths in chemistry and materials science. And it is gradually developing new strengths in the application of nanoscience to biotechnology and the life sciences. 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. It also means that institutions, policy makers and funders need to develop and extend programmes that encourage cross-disciplinary collaboration and avoid the creation of research siloes that classify projects as either physics, chemistry, biology or other traditional disciplines.

It is no coincidence that the first label to describe the field as a whole was nanotechnology rather than nanoscience. Although this term was coined decades before the tools of nanoscience would enable practical commercial nanotechnologies, a guiding principle of the field has been that these tools would help us make the world a better place. This is not to say that there shouldn't be continued and robust support for curiosity driven 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 that exist 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 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 get from more traditional physics, chemistry or biology programmes. ■

[Appendices]

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 of articles in the Science Citation Index (SCI) database, with copyright years of 1997 to 2016, resulted in 1,372,510 papers. The cut-off date for data retrieval is June 16, 2017 and terms used for the search include nano, self-assemble, 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 Nanoscale Science and Technology held in the end of May, 2017. Individual interviews were conducted via phone by Nature Research staff in early June, 2017.

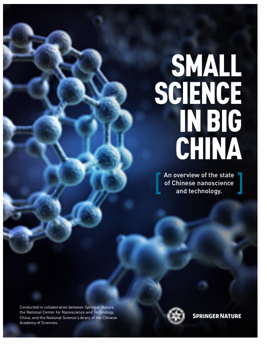
Appendix 2 | Introduction to the Nano database

Nano.nature.com, known as Nano, 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 contains at least one feature with a dimension in the range of 1 to 100 nm. In parallel, data indexes 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 nanotechnology experts from primarily 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 published in these 30 journals from 2014–2016 were analysed to provide insights of the nanotechnology trend described in this whitepaper.

Journal titles covered for this analysis

Publisher	Journal	Publisher	Journal
AAAS	*Science*	Nature Research	*Nature Materials*
ACS	*ACS Nano*	Nature Research	*Nature Medicine*
ACS	*Chemistry of Materials*	Nature Research	*Nature Nanotechnology*
ACS	*Journal of the American Chemical Society*	Nature Research	*Nature Photonics*
ACS	*Nano Letters*	Nature Research	*Nature Physics*
APS	*Physical Review Letters*	PNAS	*PNAS*
Elsevier	*Biomaterials*	RSC	*Nanoscale*
Elsevier	*Materials Today*	Springer	*Journal of Nanoparticle Research*
Elsevier	*Nano Energy*	Taylor & Francis	*Nanotoxicology*
Elsevier	*Nano Today*	Wiley	*Advanced Energy Materials*
Elsevier	*Nanomedicine: Nanotechnology, Biology and Medicine*	Wiley	*Advanced Functional Materials*
Nature Research	*Nature*	Wiley	*Advanced Healthcare Materials*
Nature Research	*Nature Chemistry*	Wiley	*Advanced Materials*
Nature Research	*Nature Communications*	Wiley	*Angewandte Chemie International Edition*
Nature Research	*Nature Energy*	Wiley	*Small*



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