Physics in China

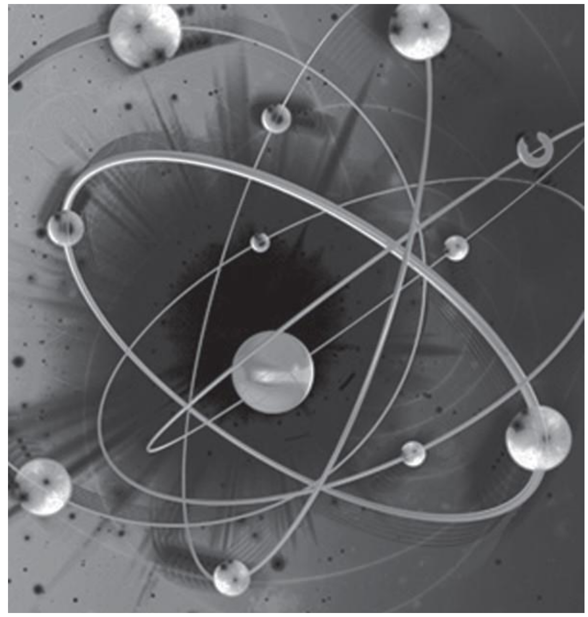
In its range and depth, physics in China is much like physics in other big, technologically advanced countries. The historical, political, and social contexts, however, are China's own.

By Charles Day

China's recent rise in physics has been remarkable. In 1986, a full decade after the wrenching experience of the Cultural Revolution, Chinese physicists published just four papers in *Physical Review Letters*. By 1996 the total had risen to 28; by 2006 it had reached 202, about the same tally as Italy or Spain.

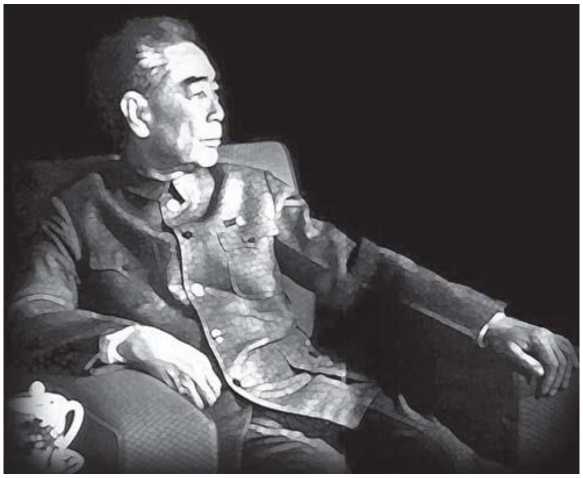
Quality has risen along with quantity. Since their publication, those four papers of 1986 have accumulated an average of 25 citations each. Last year, Thomson Reuters declared a Chinese paper[1] as one of the hottest of the year. The paper, by Chen Xianhui of the University of Science and Technology of China (USTC) in Hefei and his collaborators, reported superconductivity at 43 K in a newly discovered iron-based material. It already has 100 citations. In China, surnames come first, and I will observe that custom below.

Chen's paper and others of the past few years spring from new and refurbished laboratories full of new equipment. Oxford Instruments, a leading supplier of cryostats and other high-tech tools for R&D, has seen its sales in China jump by 78% in the past three years. China has also been building new research facilities. On the shores of Daya Bay, 50 km north of Hong Kong, contractors are nearing the completion of the Daya Bay Reactor Neutrino Experiment. The $100-million project aims to measure *theta*$_{13}$, a crucial, near-zero parameter of neutrino oscillations. At Dome A, an Antarctic plateau 4 km above sea level, China is developing plans to build a permanent observatory in one of the world's last best unexploited sites for optical and IR astronomy.



The prospects for physics in China could depend on how it makes use of its greatest resource, its people. And in that respect, the challenges that lie ahead for China are not so much in funding but in creating an intellectual climate in which imagination and ingenuity, not just hard work and skill, can develop and flourish.

With a population of 1.3 billion and an economy close to overtaking Japan's as the second biggest in the world, China seems set to become a front-rank nation in physics. Although its expenditure on science remains lower than that of the US and the EU, both in absolute terms and per capita, it's catching up quickly. According to a recent report from the US National Science Board, China has already surpassed the US in the number of researchers.



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Indeed, the prospects for physics in China could depend on how it makes use of its greatest resource, its people. And in that respect, the challenges that lie ahead for China are not so much in funding but in creating an intellectual climate in which imagination and ingenuity, not just hard work and skill, can develop and flourish.

This article is based on two trips I made to China, in October 2008 and December 2009. The research laboratories I saw are little different from their counterparts in the West, except, in some cases, in their newness. But China is different from the West— and not just in its distinctive culture and long history. Rapid economic growth and a high degree of central government control have created a unique context for physics. Describing that context is the aim of this article.

A brief history

If by modern science one means an enterprise characterized by journals, professional societies, and research laboratories, then physics and other sciences began to modernize only when the last imperial dynasty, the Qing, was overthrown in 1911. By 1937, when Japan invaded China outright, science in China had acquired many of the qualities and trappings that a visiting researcher from Europe or the US would recognize as modern.

The key instigators of that transformation were young men who saw science as a cornerstone of a strong, modern, and independent China. Many of them took advantage of a fund established in 1907 by President Theodore Roosevelt's administration to redress America's exaggerated claim of damages in the aftermath of the Boxer rebellion of 1900. The same fund paid for the foundation of Tsinghua University in Beijing.

As recounted by historian Wang Zuoyue of the California State Polytechnic University in Pomona, the "Boxer fellows" adopted a sophisticated, multipronged approach.[3] In 1914–15 while the fellows were students in the US, they formed the Science Society of China and published a journal called *Kexue* (Science). After the first fellows graduated and returned to China, they courted wealthy patrons, published popular articles, and persuaded politicians to support science. China's first modern laboratory, Nanjing's Biological Institute, was established by the society in 1922.

War stopped that promising start. Japan's defeat in 1945 after a devastating eight-year occupation was followed by a four-year civil war in which Mao Zedong's Communists and Chiang Kai-shek's Nationalists vied for hegemony. After the Communist victory in 1949, the prospects for physics and science were uncertain. Mao accepted that science was needed for China's progress and prosperity. He did not, however, fully trust scientists. His revolution was a struggle of peasants against the bourgeoisie and other "exploiting classes." Scientists were manifestly not peasants.

In 1954 the Soviet Union refused to help China build an atomic bomb. Soon after, China embarked on its own Manhattan project, which entailed not only developing nuclear weapons and ballistic missiles but also establishing an extensive national research enterprise. Still, science's newfound indispensability did not spare some scientists, including physicists, from persecution during the Anti-Rightist Movement of 1957.

In 1964 premier Zhou Enlai issued a report to the National Congress that foreshadowed the Chinese government's current attitude toward science. Zhou's report identified four areas, known later as the Four Modernizations, in which China needed to make progress: agriculture, industry, national defense, and science and technology. In his report Zhou also noted that science and technology are essential to the other three areas, necessary for both socialist and capitalist economies, ideologically neutral, and helpful to all the world's nations and peoples.[4]

Zhou's vision of prosperity driven by ideologically neutral science was postponed. In 1966 Mao, fearing his grip on power was slipping, launched the Cultural Revolution. In its violent first three years, scientists, doctors, shopkeepers—people, that is, with bourgeois occupations—were denounced and sent into the countryside to work alongside peasants to grow crops and raise livestock. Science did not die, however. During the Cultural Revolution, China launched a satellite and exploded a hydrogen bomb (see "The Chinese Nuclear Tests, 1964–1996" by Tom Reed, PHYSICS TODAY, September 2008, page 47). Rusticated physicists retained their knowledge. By 1972, when PHYSICS TODAY published its first survey of physics in China, research had been reestablished with a strong emphasis on applied fields (see "Physics in China" by Gloria B. Lubkin, PHYSICS TODAY, December 1972, page 23).

Mao's death in 1976 led to an internal power struggle from which Deng Xiaoping emerged as China's paramount leader. Deng, like Zhou, recognized the importance of science and technology. In a speech at a national science conference in 1978, he deftly absolved scientists of ideological taint by redefining them: "Intellectuals are part of the working class," he declared. "Those who work with their brains are a component of those who work."

Deng's successors, Jiang Zemin and Hu Jintao, who were both trained as engineers, continued his policy. Three years ago China issued the 15-Year Medium- to Long-Term Plan for the Development of Science and Technology. As if echoing Zhou, the plan places science and technology at the heart of China's economy. Among its goals, the MLP calls for China to invest 2.5% of its gross domestic product in R&D by 2020 and to make technology account for more than 60% of economic growth (see "China's 15-Year Science and Technology Plan" by Cong Cao, Richard P. Suttmeier, and Denis Fred Simon, PHYSICS TODAY, December 2006, page 38). According to the National Science Board, knowledge- and technology-intensive industries contributed 23% of China's GDP in 2007.[2] (The figure for the US was 38%.)

Science has indeed boosted China's prosperity. In 1984, 11 researchers from the Computer Science Institute of the Chinese Academy of Sciences (CAS) in Beijing founded a small computer company called Lianxiang. The company's "killer app" was an algorithm that made it easy to enter Chinese characters with a standard keyboard. By 2005 the company, under its new name Lenovo, had grown so much that it could buy IBM's entire PC-manufacturing division. The CAS remains the company's largest shareholder.

Lenovo was founded with seed money from the Computer Science Institute. ZTE Corp, a large manufacturer of telecommunications equipment founded in 1985, sprang from China's aerospace ministry. By contrast, the more recently founded Suntech Power, a world leader in photovoltaic solar cells, got its start in 2001 in much the same way as high-tech companies in the US do: when a founder persuades investors to back an idea.

The MLP's emphasis on technology-led growth leaves room for fundamental research, as

China's current premier, Wen Jiabao, made clear in a 2008 interview in *Science*:

Personally, I attach great importance to research in fundamental sciences because I believe that no applied or developmental research can do without basic research as the wellspring and driving force. But, in this world of ours, often because of material gains and immediate interests, it is easy to neglect basic research. This should be avoided.[5]

Funding physics

Physicists at China's top universities benefit from several funding sources, of which the biggest is the Ministry of Science and Technology (MOST). The ministry coordinates and implements China's national science priorities on the largest scale—that is, deciding which broad areas, such as nanotechnology and quantum information, to focus on and which universities should host laboratories and facilities.

The Chinese Academy of Sciences was founded in 1949. Like its predecessor in mainland China, the Academica Sinica, and its principal model, the USSR Academy of Sciences, the CAS both serves as a professional organization for the nation's best scientists and conducts research at its own specialist institutes. The CAS institutes, which number about 100, span the full range of natural sciences, including all branches of physics.

For example, MOST funds the USTC's Hefei National Laboratory for Physical Sciences at the Microscale. The lab's scope is broad: Quantum information, protein folding, and functional nanomaterials are just three of its several research areas. MOST also funds the National Laboratory of Solid State Microstructures at Nanjing University. Despite their similar names, the two labs are complementary. Nanjing's focus is on phenomena that take place on larger, 100-nm to 1-µm scales, such as surface plasmons, photonics, crystal growth, and device physics.

To fund smaller, individual research projects, Chinese physicists apply to the National Natural Science Foundation of China (NSFC). Grants are available in several broadly and succinctly defined areas, as illustrated by last year's guidance for grants in fluid mechanics:

Applications in fluid mechanics should pay attention to studies on the laws and mechanisms governing complex flows (including non-steady flow, turbulence and multi phase flow problems). The Division will continue to support studies on fluid mechanical problems in aerospace and aviation, ship and marine engineering, civil and hydrological engineering, and chemical engineering, and strengthen studies on fluid mechanical issues in energy, environment, and other high-tech and advanced technology areas.

Grants are valued up to 600,000 renminbi (RMB), which works out to about $88,000 using the nominal exchange rate. Like its near-namesake in the US, the NSFC evaluates proposals by peer review.

Provincial and local governments also fund science, as the USTC exemplifies. Anhui, the province where the USTC is situated, provides grants for its students to attend the elite university. Suzhou, a city in neighboring Jiangsu Province, donated land on its outskirts for the USTC's new Software College.

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The CAS is not subordinate to MOST. Both organizations come under China's highest administrative body, the State Council. Whereas MOST is a ministry, the CAS and NSFC are institutions. All three organizations carry out the country's scientific priorities. As members of China's science elite, individual CAS academicians influence science policy, but, as in the US, the government sets and implements it.

Researchers at a CAS institute—say, the Institute of Physics in Beijing—typically have well-equipped labs and access to graduate students from the CAS graduate school, but no teaching responsibilities. The IOP, whose focus is on experimental and theoretical studies of condensed matter, is at the forefront of elucidating the properties of the recently discovered iron-based superconductors (see PHYSICS TODAY, May 2008, page 11). The current highest T_c, 55 K, was achieved at the IOP.

Universities

As places where students learn and where scholars pursue their research, universities in China have long been subject to the interest and influence of the prevailing government. China's first true university, Peiyang University (now known as Tianjin University), was founded in Tianjin in 1885 during a short-lived burst of political and cultural reform in the waning years of the Qing dynasty. China's most venerable universities were founded within the next two decades.

Today, China's universities fall roughly into a two-tier system. In the top tier are the 100 or so national universities run by the Ministry of Education. Below them are the 2000 or so universities run by China's 22 provinces and five autonomous regions. (Universities in China's two special administrative regions, Hong Kong and Macau, are not part of the mainland system.) Determined to see its universities compete with those of the West, China has embarked on several waves of funding increases and reorganizations. The most recent initiative, announced last October, was the creation of the C9 League, an alliance of the nine best universities.

An older, wider-reaching initiative is to reverse the Soviet model of discipline-specific colleges. Zhejiang University in Hangzhou, for example, has reabsorbed its medical school. Nanjing University is in the process of merging with an engineering school. As they merge and expand, China's universities are building new campuses. Fudan's new campus is on a plot of reclaimed industrial land near the Yangtze River. The campus, including the brandnew physics building, pays architectural homage to Shanghai's Bund, a street of imposing 19th-century buildings on the embankment of the city's other river, the Huangpu.

Money for universities also comes from sources outside the central, provincial, and city governments. Tsinghua University's new Research Center for Nanotechnology was funded in part by a donation from Foxconn, a Taiwan-based manufacturer of computer components. The Kavli Foundation has established two institutes in China, the Kavli Institute for Astronomy and Astrophysics (KIAA) at Peking University and the Kavli Institute of Theoretical

Physics China (KITPC) on a nearby CAS campus.

What sort of education does an undergraduate receive at China's universities? It's hard to answer that question based on a brief visit. Certainly, China's traditional respect for teaching remains strong. Tsinghua and Zhejiang universities, for example, have large new buildings devoted solely to physics teaching labs. There, students conduct classical experiments, such as building and testing a Wheatstone bridge, but they also experiment on superconductors. And it barely needs pointing out that the best graduate schools in the US and Europe recruit Chinese students.

International collaborations

Although MOST, the CAS, and the NSFC support national goals, China also seeks international collaborations. The Daya Bay Reactor Neutrino Experiment, led by the Beijing-based Institute of High-Energy Physics, is an international collaboration. Its roster of partners includes two US national laboratories—Brookhaven and Lawrence Livermore— 14 US universities, two Russian institutions, one Czech university, and two Taiwanese universities. The US is paying about half the cost.

China's efforts in astronomy illustrate how the country's international collaborations align with national interests. China currently lacks the experience to build observatories at the leading edge of technology, such as the European Space Agency's recently launched IR satellite, *Herschel*. Acquiring that experience through independent effort would take time and risk China's falling further behind. To catch up, China is pursuing a mix of more modest, homegrown advances and participation in international projects.

China's recently commissioned LAMOST telescope will survey the sky in a fashion similar to that of the Sloan Digital Sky Survey—that is, it will automatically determine the spectra (and therefore red-shifts) of the stars and galaxies over large swaths of sky. LAMOST's primary mirror has four times the area of the SDSS telescope's, and its focal-plane CCDs are more efficient and more sensitive. LAMOST's performance is limited somewhat by the modest number of truly clear nights at its site in Hebei Province. Still, it's expected to produce the most complete catalog of stellar motions in our galaxy and with it the most accurate map so far of the Milky Way's distribution of gravitational matter, both baryonic and dark.

The LAMOST telescope has provided China with valuable experience in the production and operation of segmented mirrors. As this article goes to press, China is negotiating the terms of its participation in the Thirty Meter Telescope, a US–Canadian project to build a huge segmented-mirror observatory on Mauna Kea in Hawaii.

In the TMT, China will play a minority role. But in the case of the proposed observatory at Dome A, China will lead. Site characterization is already under way. The challenges of observing remotely in the Antarctic are formidable. Power needs to be generated locally, and data have to be retrieved across shifting, breaking ice sheets. In taking up those challenges, China has the field largely to itself.

China is also determined to become a hospitable and profitable place for international visitors. Two examples illustrate that trend. Zhejiang University and Rice University in Houston, Texas, have set up the International Collaborative Center on Quantum Matter. The London Center for Nanotechnology and the Max Planck Institute for the Physics of Complex Systems in Dresden, Germany, also participate. The idea is to foster collaboration on projects of mutual interest through workshops and long visits. At Peking University, the two-year-old KIAA also conducts international workshops. Doug Lin, its founding director, says the institute will serve as a place where Western and Chinese researchers can collaborate and learn from each other.

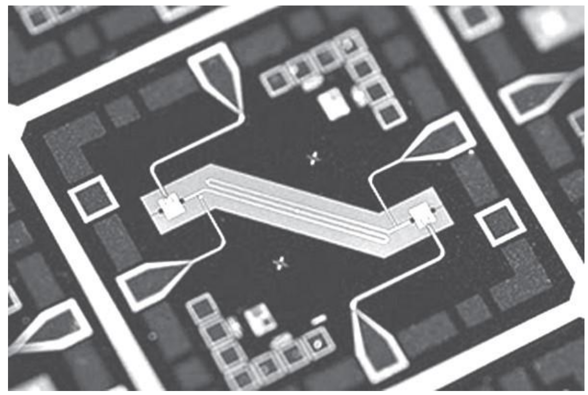
Unfortunately, China's desire to forge partnerships with the US is being frustrated by US immigration policy. The procedure a Chinese physicist must follow for obtaining a US visa is burdensome, time consuming, and uncertain—to the point that many Chinese physicists have given up trying to visit the US. Obtaining a US visa can take three months. By stark contrast, Chinese physicists can obtain an EU visa within four business days without having to apply in person. US visitors to China can obtain a visa in one day.

Human factors

China's drive to excel in physics, matched by Chinese physicists themselves, has resulted in a well-funded and highly competitive research environment, not unlike the West, but with additional Chinese characteristics. Some universities in China, not necessarily the best ones, reward the authors of papers published in *Nature*, *Science*, and other high-impact journals with bonuses comparable to one's annual salary. The pressure to publish is probably behind the lower-than-average acceptance rate of Chinese papers in *Applied Physics Letters* and other journals.

Competition is especially keen when it comes to attracting talented Chinese physicists back to China. The competition is twofold: between China and the West and among Chinese institutions. Universities and institutes in Shanghai and Beijing can point to their cities' wealth, size, and importance as inducements. Zhejiang University is in Hangzhou, a city described by visitors from Marco Polo to the authors of modern travel guides as among the most beautiful in China. Hefei's USTC, by contrast, touts its small size and low housing costs. To tip the balance in favor of their universities, some department chairs have the flexibility to appoint young returnees to full professorships. In the end, research opportunities are likely to weigh heaviest. Ding Hong left Boston College for the IOP in 2007 for "better research support, including funding and human resources, and for a bigger field of play."

The intense competition to get results leaves some Chinese physicists complaining that they no longer have time to think. When a research goal is clear—say, catching up with the US in condensed-matter implementations of quantum computing— hard, determined effort may result in success. But without the time to think, creating brand-new fields of endeavor is harder. China's contributions to understanding the new iron-based superconductors and to extending the practical applications of quantum cryptography—to cite two examples—are impressive. The fields, however, originated outside China.



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On the other hand, a comparison with the US suggests that China might simply need to wait to cultivate truly original research. By the 1870s the US economy had grown to rival those of the UK, France, and Germany. Wealthy US industrialists founded and donated money to universities. At the end of World War I, the US economy was the biggest in the world, yet talented American undergraduates still left the US to study in Europe. Only in the 1930s did the US become the preeminent scientific superpower. The influx of Jewish scientists from Nazi Germany certainly helped, but those exiles found extensive infrastructure and funding opportunities when they arrived. They also found talented, home-grown colleagues.

Waiting for its investments in science to pay off might not be enough to ensure that China becomes a scientific superpower. As some of China's leaders recognize, change is needed in the education system. Guo Shuqing is the president of the China Construction Bank, one of the biggest financial institutions in the world. He also serves on the powerful central committee of the Chinese Communist Party. Writing last year in the op-ed pages of the *Financial Times*, Guo enumerated the obstacles that China must overcome to further its development. Third on his list is this:

Development of human capital is vital for China's future, but it is far behind developed countries in education and training. Our education system is not conducive to encouraging innovation. This will hinder high-level and sustainable development.

China's education system is highly competitive. A three-day national examination, the *gaokao*, determines who gets into the best universities. The preparation required to succeed in the *gaokao* is so intense and extensive that students have little time to develop the habit of following where their natural curiosities and passions might take them.

I am grateful to my generous and attentive hosts in China: Jin Xiaofeng of Fudan University, Wang Yupeng of the Institute of Physics, Zhu Bangfeng of Tsinghua University, Xue Suijian of the National Astronomical Observatories of China, Doug Lin of the Kavli Institute for Astronomy and Astrophysics, Li Youquan of Zhejiang University, Wang Xiaoping of the University of Science and Technology of China, and Wang Mu and Li Jianxin of Nanjing University. I also thank Zhang Fuchun of Hong Kong University and Zhao Zuyu of Janis Research Co for their invaluable help and advice.

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FOOTNOTES

1. X. H. Chen, T. Wu, G. Wu, R. H. Liu, H. Chen, D. F. Fang, Nature 453, 761 (2008) [MEDLINE].
2. National Science Board, *Science and Engineering Indicators 2010*, National Science Foundation, Arlington, VA (2010); available at http://www.nsf.gov/statistics/seind10.
3. Z. Wang, *Osiris* 17, 291 (2002).
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5. H. Xin, R. Stone, *Science* 322, 363 (2008).

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Charles Day is a senior editor at PHYSICS TODAY.

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