ESSAY

The end of the science superpowers

Could the end of US world dominance over research mark the passing of national science giants, ask **J. Rogers Hollingsworth**, **Karl H. Müller** and **Ellen Jane Hollingsworth**.

From around 1735 until 1840 France led the world of science. This was the era of Antoine Lavoisier, Pierre-Simon Laplace and Claude Berthollet, with great advances in physics, mathematics, physiology and medicine. Centralization of the state and the education system in France, combined with a robust economy, made for a renowned science system. But ultimately, the centralized system led to rigidity and decline in the quality of science.

Next the nexus shifted to Germany, from the middle of the nineteenth century until the 1920s. This period saw the birth of a new type of research-oriented university, the creation of well-equipped laboratories, the emergence of numerous institutes, such as the Kaiser Wilhelm (later Max Planck) Institutes, and the growth of science-based industries such as dyes, pharmaceuticals and vaccines. In the first eleven years of the Nobel prizes, thirteen German scientists received awards in chemistry, medicine or physics — many more than any other country.

At the beginning of the twentieth century, the hub shifted to Britain. Over the next half century, scientific funding from government and industry rose, the university system was vigorous, and the country boasted numerous Nobel prizewinners: physicists Joseph John Thomson, the father and son team of William and Lawrence Bragg, Paul Dirac, James Chadwick and John Cockcroft; biologists Archibald Hill, Frederick Hopkins, Charles Sherrington, Edgar Adrian, Henry Dale and Howard Florey; and chemists Frederick Soddy and Alexander Todd. Then with the demise of the British Empire and the weakening of the British economy, this system of science declined too. The United States picked up the baton and holds it still.

The United States emerged from the Second World War as the world's economic superpower, facilitating the dominance of its system of science. Since then, American scientists have received more than half of the most prestigious awards in the sciences, such as Nobel, Lasker, Horwitz and Crafoord prizes. US researchers dominate scientific journals, accounting for more than 50% of the top 1% of cited papers and around 30% of all published papers. The United States also attracts talented young scientists for advanced training, echoing the migration of thousands of Americans to German universities during the second half of the nineteenth century and the later flow to Britain of scientists from across the British Empire.

Yet history suggests that the United States has no cause for complacency. Patterns in the rise and fall of former leading scientific nations imply that, unless serious steps are taken, the United States could look back on the early twenty-first century as the peak of its scientific dominance. Each former giant of science emerged when the society's economy became extraordinarily robust by world standards. As the French, German and British economies declined relative to the world's most dynamic centres of fiscal growth, so did their science systems. The independence and flexibility that once characterized their research systems diminished markedly. Each former scientific power, especially during the initial stages of decline, had the illusion that its system was performing better than it was, overestimating its strength and underestimating innovation elsewhere. The elite could not imagine that the centre would shift.

Meanwhile, fundamental changes over the past few decades in economics, funding, communication, organizational structure, and specialization could mean that the United States is not simply poised to cede its scientific throne to a national successor such as China. Rather, the end of America's era as the scientific hegemon could also be the end of the era of scientific hegemons.

> "The decline of the US economy is facilitating the strengthening of science elsewhere."

State of the union

Since 1945, the number of scientific papers and journals in highly industrialized societies — particularly the United States — has risen almost exponentially, while the proportion of the workforce in research and development and the percentage of gross national product devoted to it have grown more modestly. Yet the rate at which truly creative work emerges has remained relatively constant. In terms of the scale of research efforts to make major scientific breakthroughs, there are diminishing returns.

Americans have led the way in the emergence of 'big science', with, for example, the Manhattan Project, the Jet Propulsion Lab and the Lawrence Livermore, Argonne and Brookhaven national laboratories. Indeed, in all fields there has been a shift to collective research. One of the virtues of large-scale science is the ability to organize sizeable groups with different skills, ideas and resources. Teams produce many more papers than individuals do, leading to the boom in science publishing. In recent decades, the number of authors per paper has more than doubled. Moreover, team-authored papers are 6.3 times more likely to receive at least 1,000 citations (S. Wuchty, B. F. Jones and B. Uzzi *Science* **316,** 1036–1039; 2007).

In some fields, this transformation towards big science has built in irreversible constraints. During the past half century, universities, research institutes and pharmaceutical companies have swelled in number. Many universities have become increasingly bureaucratic and fragmented, with huge departments constructed like silos. As a result, many scientists have considerable difficulty in communicating across fields. The number of scientists, postdocs, research assistants, technicians and secretaries has mushroomed. To manage large scientific organizations, multiple levels of management have developed, with leaders of subgroups, chairs of departments, associate deans, deans of colleges, provosts for academic affairs, chancellors and vice-presidents for research, for business affairs and for legal affairs.

In some respects, the research segments of many US universities have become like holding companies. As long as researchers can bring in large research grants and pay substantial institutional overhead costs, universities are happy to have the income. Granting agencies and universities, realizing that this kind of structure has become dysfunctional, have made serious efforts to reduce the number of managerial levels and to develop matrix-type teams to minimize organizational rigidities. However, organizational inertia hampers these efforts.

With the ballooning of publications, universities, funding agencies and reviewers have less time to evaluate scientific papers carefully, and rely more and more on quantitative measures based on citation statistics. Scientists are increasingly assessed by the number of papers


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they have authored. At the same time, the increasing commercialization of science has tended to emphasize short-term scientific horizons. All these factors threaten the future quality of American science.

Altering the dynamics

If funding agencies and leaders in the scientific community emphasize commercialization of science in large-scale research environments, the US system risks losing its flexibility and its capacity to make major fundamental discoveries as bases for new applications some 40 or 50 years hence. Often, knowledge for major discoveries is created during a largely unanticipated and unplanned stage of research and produces various unintended consequences.

Excellence in science requires nimble, autonomous organizations — qualities more likely to be found in small research settings. Dozens of scientists who made significant advances did so in organizations with fewer than 50 full-time researchers. In the recent past, some of the most creative small centres were the Rockefeller University in New York, the Salk Institute in San Diego, California, the Basel Institute for Immunology in Switzerland, the Laboratory of Molecular Biology in Cambridge, UK, and various Max Planck Institutes in Germany. In the past decade Nobel prizes have been awarded to scientists for work done in relatively small settings: Günter Blobel (physiology or medicine), Ahmed Zewail (chemistry), Paul Greengard (physiology or medicine), Andrew Fire (physiology or medicine), Roderick MacKinnon (chemistry) and Gerhard Ertl (chemistry).

America's science system could enhance its performance by creating several dozen small research organizations in interdisciplinary domains or in emerging fields, modelled along the lines of the organizations mentioned above. In recent years, there have been several such efforts — the Howard Hughes Medical Institute's Janelia Farm in Chevy Chase, Maryland, the Santa Fe Institute in New Mexico, the Institute Para Limes in Warnsveld, the Netherlands, and the new Institute for Quantum Optics, Quantum Nanophysics and Quantum Information in Vienna.

Last of the giants?

The decline of the US economy relative to those of the rest of the world is facilitating the strengthening of science elsewhere. An evolving multi-polar world economy is leading to multiple centres of science — the United States, the European Union, Japan, China, Russia and possibly India. The increasing wealth of several of these societies is enabling them to lure back many younger scientists trained abroad in the world's leading institutions.

A remarkable aspect of this change has been the rapidity with which China has emerged as an important science power. For example, China was fourteenth in the world in production of science and engineering papers in 1995; by 2005, as the Chinese economy boomed, it was fifth in the production of papers, according to Thomson Reuters ISI. By 2007 it was second. Between 1985 and 2005, the number of natural sciences and engineering doctoral degrees awarded in China increased sevenfold, so that by 2005 China was third in the world. Moreover, in recent years more and more senior expatriates have been returning to China.

The mobility of researchers and their funds across continents is rising rapidly: Europeans are moving in larger numbers to Asia and vice versa. Leading journals with articles from more countries play a major part in the governance of scientific practices and the coordination of scientists across the globe. Overall, there is more uniformity in methodology, training and publication, with open-access publishing and the Internet contributing to a globalized science system.

All in all, it seems unlikely that we will witness another unrivalled scientific behemoth in the mould of France, Germany, Britain and the United States. ■

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