THE RISE AND DECLINE OF HEGEMONIC SYSTEMS OF SCIENTIFIC CREATIVITY

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Abstract

We analyze scientific creativity at the level of the society by focusing on the rise and decline of creativity at the level of the nation state during the past 275 years. We note outstanding individuals, departments and organizations in the context of the hegemonic science systems they represented and list organizational and institutional factors facilitating and hampering major discoveries. The most highly creative systems of science have been embedded only in those societies that were economic, political, and military hegemons. There has been a succession of scientific hegemons: France, Germany, Britain, and the United States. Scientific hegemons dominated multiple scientific fields and established the standards of excellence in most scientific fields. Their language became the major one used in scientific communication and their scientific elite were the most prominent in the world of science. They attracted more foreign young people for training than any other country. Their scientific culture tended to reflect the society's culture. We examine factors contributing to each scientific hegemon's eventual decline and graph their trajectories over time. We examine hindrances to the continued high performance of the US science system and make recommendations for enhancing future performance.

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Keywords

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There is a long tradition of addressing creativity at the level of the society, whether it be the ancient Greek city states, sixteenth-century Florence, the French Enlightenment, or other societies. In order to get a fresh perspective on creativity in the contemporary world, this discussion extends the tradition by focusing on the rise and decline of creativity at the level of the nation state during the last 275 years. Despite our focus on the societal level, we recognize that most acts of creativity occur at the level of the individual. But by aggregating acts of creativity, it becomes possible to analyze creativity at the level of (1) a society, (2) an organization (e.g., Bell Labs; the Laboratory of Molecular Biology in the United Kingdom; the Max-Planck Institutes in Germany; Rockefeller University in the United States), and (3) a department (e.g., physics at the University of Göttingen in the 1920s; the Cavendish Laboratory in Cambridge during much of the twentieth century).

Since the mid-eighteenth century, the most highly creative systems of science have been embedded only in those societies that were economic, political, and military hegemons (from the ancient Greek word *hegemon*, meaning ‘leader’). A hegemonic power is one that exercises political, economic, and military supremacy over all other powers. Hegemonic power is a relative concept, always varying with its relationship with other powers. It was the economic, political, and military hegemonic power that gave birth to creative scientific hegemons.

A scientific hegemon dominates multiple scientific fields and establishes the standards of excellence in most scientific fields. Its language is the major one used in scientific communication and its scientific elite are the most prominent in the world of science. It attracts more foreign young people for training than any other country. Its scientific culture tends to reflect the society’s culture. Scientific hegemons are embedded in societies that are economic, political, and military hegemons, but not all political, economic and military hegemonic powers have a hegemonic scientific system. Modern hegemonic scientific systems exist only in societies that are political, economic, and military hegemons.

The process by which scientific hegemons emerged as well as declined varied from society to society—though the underlying explanation was the same in each society. When their system had begun to decline, the elites in scientific hegemons often failed to understand this; indeed they tended to believe that their system was continuing to perform extraordinarily well. It was only under retrospective analysis that their system of science was observed to be already in relative decline. Over the past 275 years, scientific hegemons declined partly because the society in which they were embedded overextended itself in foreign adventures that were unsustainable economically and militarily.

Figure 1 is a representation of the rise and decline of four hegemonic systems of science since the middle of the eighteenth century: French, German, British, and American.

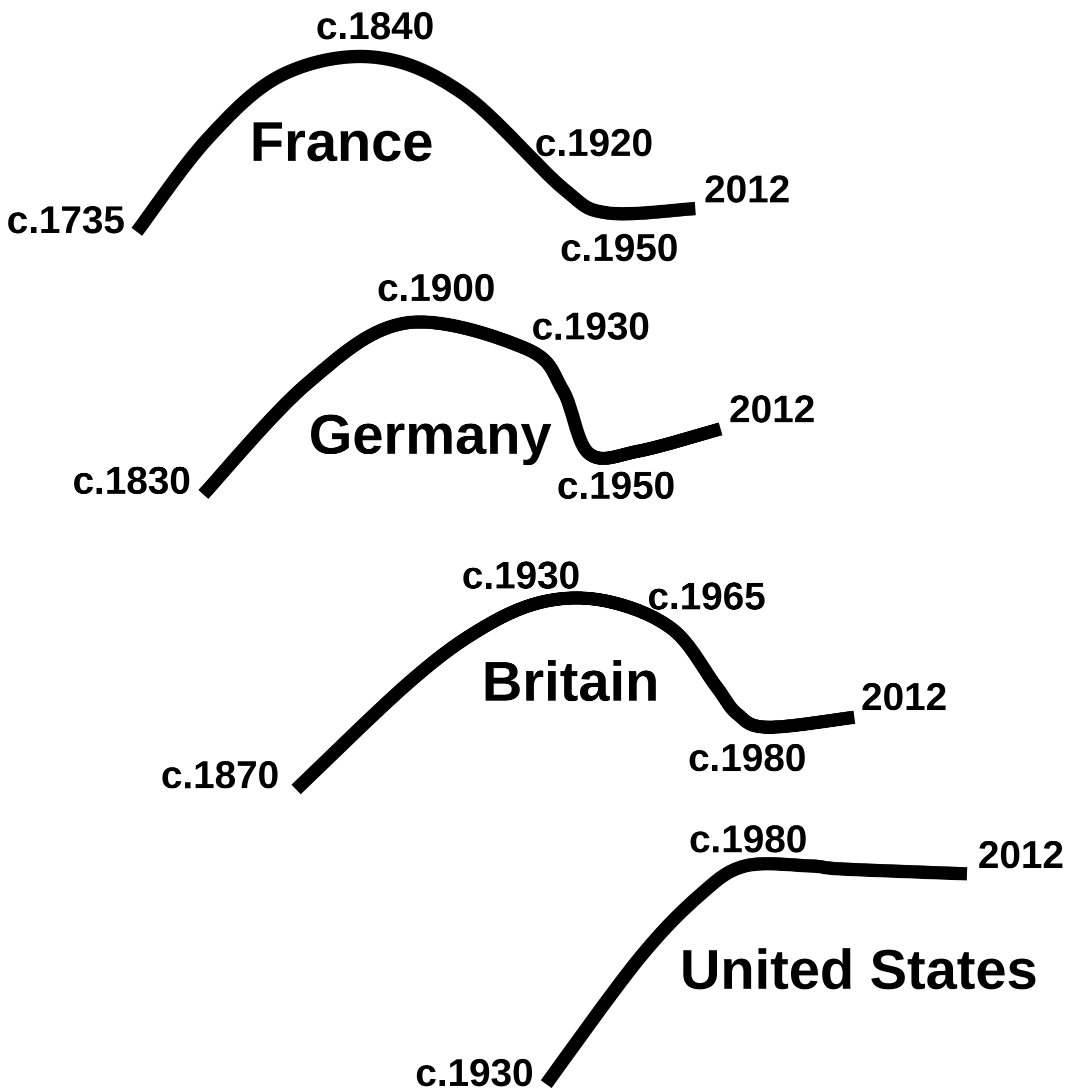

Figure 1. The rise and decline of hegemonic systems of science

French hegemony

From around 1735 until the mid-nineteenth century, France led the world in scientific creativity—particularly in the fields of mathematics, physics, physiology, clinical medicine, zoology, and paleontology. A few of the most prominent French scientists of this period are listed in table 1.

As France was a great power during the latter part of the eighteenth century, it is not surprising that it became a scientific hegemon. The world's leading scientific journals were published in France; the major scientific language was French; many of the world's most accomplished scientists were French; and large numbers of young people from all over Europe went to France for training. However, the turmoil brought about by the French Revolution and the military adventures of Napoleon Bonaparte had long-term negative effects on the military, economic, and scientific influence of France. Of course, the decline of France's distinction in science did not occur all at once. Indeed throughout the nineteenth century and even through the early years of the twentieth century, many of the world's most eminent scientists were French.

Table 1. Distinguished French Scientists 1770–1850

Claude Bernard
Claude Berthollet
Charles-Édouard Brown-Séquard
Jacques Charles
Antoine-Laurent de Jussieu
Pierre Laplace
Auguste Laurent
Antoine Lavoisier
René-Théophile Laennec
Jean-Baptiste Lamarck
Joseph Louis Gay-Lussac
François Magendie
Étienne Louis Malus
Charles Messier
L.B. Guyton de Moreau
Urbain Jean Joseph Le Verrier

France's role as a scientific hegemon did not decline simply because of its relative decline in military, economic, and political power. There were inherent contradictions in French society, which had profound implications for science. Part of the problem was the centralization of French government. Before and somewhat after the French Revolution, the centralization of France was significant in accelerating the rapid growth of France's role in world affairs—including its system of science. But during the nineteenth and on into the twentieth century, centralization had an adverse effect on France's ability to adapt to many of the radical innovations occurring elsewhere in the world, especially in the rest of Europe.

This was of course not true of all aspects of French society. Indeed in the first half of the nineteenth century, outstanding scientific research occurred in the Collège de France in Paris and in several of the *grandes écoles*. Moreover, even as basic science in France declined during the nineteenth century, the society excelled in the development of large-scale technological systems. This was a legacy of Jean-Baptiste Colbert who, late in the seventeenth century, led France in making it a world leader in large-scale technological systems: a tradition which continued into the twentieth century with the development of French trains and aircraft. Colbert was a pioneer in developing applied science through government activity. As a result the French state developed a world-class system of schools to train technocrats: the École des Mines, the École des Ponts et Chaussées, the École de Génie Militaire, and the world-renowned École Polytechnique. At the École Polytechnique the dominant epistemology emphasized deductive reasoning, complemented by rigorous mathematics.

However, partly because of its heavy investment in technological training in the development of large-scale projects, the French state underinvested in the training of young basic scientists. During the past several centuries, French society long admired highly achieving individuals, but was miserly in investing in the development of individual creativity. Throughout the nineteenth and twentieth centuries, the celebration of great scientists and other intellectuals was an important part of French culture. But among the four societies discussed in this essay, none was more parsimonious and lacking in foresight than France in providing individual scientists with the financial and organizational resources they needed for excellent research.[1] From the middle of the nineteenth century, while German universities were providing world-class equipment for laboratories, some of France's greatest biomedical scientists—François Magendie, Claude Bernard, Charles-Édouard Brown-Séquard, Louis Pasteur, as well as Pierre Curie and Marie Curie—often had to work under abominable conditions. It is a tribute to the French system of education, with its emphasis on individual brilliance and creativity, that these scientists performed so well despite their inadequately developed and underfunded research organizations. Over the years, scientists in France, in comparison with those in Germany, Britain, or the United States, more often than not had to operate in crowded laboratories, to rely on obsolete equipment, and to endure periodically the deleterious effects of inflation.

Even when the French government provided ample funding for laboratories, the method of governance was highly centralized. While there was some variation in the type of state-run organizations dedicated to research—the universities, the Collège de France, hospitals, and the Musée de l'Histoire Naturelle (not a museum but a training and research center)—these different organizations enjoyed little autonomy or flexibility, which naturally hampered their capacity to make major discoveries.

Numerous accounts have described how the French university system has long been embedded in a highly centralized ministry of education that determined salaries and promotions. Letters of evaluation were often written largely by friends and mentors. Historically, there was an enormous amount of favoritism and organizational nepotism.[2] Some of France's most distinguished scientists expressed harsh criticism of the system: of its lack of funds, the mediocrity of its science, the perpetuation of antiquated disciplines and the reluctance to develop new ones, and the incompetence of administrative personnel. Pasteur, Bernard, and Adolphe Wurtz all wrote scathing reports on French science.

According to Terry Shinn, the files of applications of young people wishing to be trained as scientists became voluminous as the French government demanded information about the applicants' families. But the applications were then often filed away without any response to the applicant. In the meantime, buildings deteriorated: roofs leaked, floors flooded, and walls crumbled. There are many reports of insufficient light and lack of running water in laboratories, and, for lack of adequate storage facilities, equipment sometimes simply vanished. These conditions were obviously disincentives for young people thinking of becoming scientists, while many of those who had embarked on a career in science lost their ambition to conduct research.[3]

In areas of creative activity with few expectations of funding by the state, such as in the arts, France excelled. One has only to think of French literature, painting, and sculpture in the nineteenth century. But in science, after the first third of the nineteenth century, the centralized state stifled individual creativity, except in the service of large-scale collective projects. This, coupled with the decline of French political and economic hegemony on the world stage, diminished France's potential to remain a scientific hegemon.[4]

German hegemony

From France the world's center of scientific creativity shifted to Germany, which became the world's scientific hegemon from about 1840 to the 1920s. This was a consequence of economic prosperity and a powerful political elite with a strong military organization. From the middle of the nineteenth century until the early twentieth century, twenty prominent German research universities emerged, and Germany had a far larger number of serious research universities than any other country. The new type of German university produced many of the world's most creative mathematicians, physicists, chemists, biochemists, and biologists. Germany had the world's best-equipped laboratories and scientific institutes—such as the Kaiser Wilhelm (later Max-Planck) Institutes—and growing science-based industries in pharmaceuticals, dyes, and vaccines. In the first eleven years of the Nobel Prizes, from 1901 onwards, thirteen German scientists received awards in physics, chemistry, and physiology or medicine—many more than any other nationality.

From 1880 until 1920, German science dominated numerous fields and established new standards of excellence. The leading scientific journals of the day were based in Germany, making German the major language for scientific communication. Germany attracted more foreign young people to study in its universities than any other country. Tens of thousands of young Americans travelled to Germany in the late nineteenth and early twentieth century for advanced training—a factor that led to the transformation of research in the United States.

However, like France, fundamental contradictions were built into both the culture of Germany and its science system, particularly its high level of authoritarianism—a factor which would later place constraints on the creativity of German science. Respect for authority in society facilitated the rapid emergence of German universities, but it would ultimately be a factor in their relative decline. Because most university departments had only one professor, senior professors tended to incur heavy responsibilities for teaching across all fields in their particular discipline, limiting their ability to specialize, and heavy administrative burdens, limiting their time for research. In due course, creative research in most scientific disciplines began to level off. The increasing inability of German universities to create new disciplines necessitated the creation of the Kaiser Wilhelm Institutes in 1911, resulting in a surge of creative research, at least for a while.

The first institutes were in Dahlem, a suburb of Berlin. They were established in physics, in various fields of chemistry, and in the biological sciences—all concentrated within a few hundred meters of each other—which contributed to Dahlem becoming one of the most creative centers of science anywhere (see table 2).

Table 2. Distinguished Scientists at Kaiser Wilhelm Institutes in Dahlem

Albert Einstein (N)
James Franck (N)
Richard Goldschmidt
Fritz Haber (N)
Otto Hahn (N)
Hans Krebs (N)
Lise Meitner
Otto Meyerhof (N)
Carl Neuberg
Michael Polanyi
Axel Theorell (N)
Otto Warburg (N)
Richard Willstätter (N)

(N) = Nobel Laureate

Among those appointed to these institutes were Albert Einstein, Richard Goldschmidt, Fritz Haber, Otto Hahn, Lise Meitner, Otto Warburg, and others of great distinction. One most important attraction and facilitator of interaction among scientists at the Dahlem institutes were the 'Haber colloquia' held every Monday afternoon. Among those frequently in attendance were the scientists mentioned above; more occasional attendees included Niels Bohr, Peter Debye, Selig Hecht, Max von Laue, Max Planck, Walther Nernst, Edwin Schrödinger, and Arnold Sommerfeld. Soon there were Kaiser Wilhelm Institutes in various parts of Germany, though none as creative as those in Dahlem.

The institutes would not have been possible without the hegemonic power of the German Empire. Then Germany's political elites and military powers overreached themselves, resulting in Germany's defeat in the First World War, the loss of considerable territory, and a disrupted economy. By the early 1920s, all of these factors, combined with poor economic policies, resulted in some of the most disastrous inflation ever experienced in a modern economy. This led to the relative decline of German scientific hegemony even before the Nazis came to power in 1933.[5] Indeed, Germany's loss of status as a major power contributed to the emergence of the Nazi party in the 1920s.

Yet even in the midst of the decline of a national scientific hegemon, scientific creativity may still occur in particular centers, as was clearly the case at the University of Göttingen in the 1920s. (See table 3.) In that decade Göttingen became one of the most creative universities in the natural sciences of the entire twentieth century, encouraged by a high degree of communication among excellent scientists in diverse fields. Working there at the time were the internationally distinguished mathematicians Richard Courant, Edward Landau, and David Hilbert, and the chemists Walther Nernst, Adolf Windaus, and Richard Zsigmondy—all three of whom received Nobel Prizes for work done mostly at Göttingen. Others at Göttingen were considered to be among the world's most creative scientists during the 1920s in their fields: Heinrich Johann

Tammann in physical chemistry, Wilhelm Stille in geology, Otto Mügge and Victor Moritz Goldschmidt in mineralogy, Hans Kienle in astronomy and astrophysics, and Ludwig Prandtl, the father of modern aerodynamic theory.

Table 3. Distinguished Scientists at the University of Göttingen in the 1920s

Physicists:

James Franck (N)
Max Born (N)
Robert Pohl

Doctoral students or assistants of Born, all of whom became world leaders in theoretical physics:

Wolfgang Pauli (N)
Werner Heisenberg (N)
Enrico Fermi (N)
Maria Goeppert Mayer (N)
Pascual Jordan
Friedrich Hund
Erich Hückel
Lothar Nordheim
Léon Rosenfeld
Vladimir Fock
Egil Hylleraas
Max Delbrück (N)
Robert Oppenheimer

Others spending time in Göttingen's Physics Institute during the 1920s:

Niels Bohr (N)
Eugene Wigner (N)
Paul Dirac (N
John von Neumann
Edward Teller

Mathematicians

David Hilbert
Richard Courant
Edward Landau

Chemists

Walther Nernst (N)
Adolf Windaus (N)
Richard Zsigmondy (N)
Heinrich Tammann

Table 3 (*continued*)

Geologists
Wilhelm Stille

Mineralogists
Otto Mügge
Victor Moritz Goldschmidt

Astronomer and Astrophysicist
Hans Kienle

Aerodynamics
Ludwig Prandtl

(N) = Nobel laureate

But it was in physics that Göttingen excelled the most. Two Göttingen professors of physics became Nobel laureates: James Frank in experimental physics and Max Born in theoretical physics. Among Born's doctoral students or assistants were Wolfgang Pauli, Werner Heisenberg, Maria Goeppert Mayer, Enrico Fermi, Pascual Jordan, Friedrich Hund, Erich Hückel, Lothar Nordheim, Léon Rosenfeld, Vladimir Fock, and Egil Hylleraas. The first four later received Nobel Prizes in physics, and all the others became world leaders in theoretical physics. Max Delbruck received his doctorate under the direction of Born and would later also receive a Nobel Prize in physiology or medicine, for work in phage genetics. Robert Oppenheimer received his doctorate in physics at Göttingen, also under the direction of Born. Others who spent varying periods of time in Göttingen's physics institute during the 1920s were two more future Nobel laureates, Paul Dirac and Eugene Wigner, and John von Neumann and Edward Teller.[6]

For a short period of time during the mid-1920s, Göttingen was clearly the world's most creative center in quantum theory, but shortly thereafter multiple creative centers emerged in the same field: Copenhagen (under Niels Bohr), Paris (under Louis de Broglie and Paul Langevin), Munich (under Arnold Sommerfeld), Zurich (under Erwin Schrödinger), and Cambridge (under Paul Dirac). Göttingen's star went into total eclipse following Adolf Hitler's ascent to power in 1933. Nazi Germany and later the Soviet Union represent cases of societies that became political and military hegemons without becoming scientific hegemons, suggesting that a scientific hegemon is unlikely to emerge in a society under totalitarianism.

British hegemony

By the early twentieth century, the world hub of scientific creativity was beginning to shift from Germany to Britain. The United Kingdom had long been an economic, political, and military hegemon—with its colonial power extending across the world, and the world's most powerful navy. English now slowly replaced German as the leading scientific language. From the beginning of the twentieth century until the Second World War, funding for British science came from both government and industry, and the university system became increasingly creative, especially in Cambridge. The United Kingdom soon boasted a remarkable number of Nobelists, recognized for their creativity, a large majority of whom did their scientific work at Cambridge. Thirty-seven Nobel Prizes were awarded to scientists for work done in Britain before 1950—far more Nobel Prizes than any other country during the same half-century (see table 4).

Table 4. Scientists Receiving Nobel Prizes for Work Done in Britain Prior to 1950

Physicists

Lord Rayleigh
J. J. Thomson
Ernest Rutherford
William Bragg
Lawrence Bragg
Charles Barkla
Charles Wilson
Owen W. Richardson
Paul Dirac
James Chadwick
George Thomson
Edward V. Appleton
Patrick M. S. Blackett
Cecil Frank Powell
John Cockcroft
Ernest Walton

Chemists

William Ramsay
Frederick Soddy
Francis Aston
Arthur Harden
W. Norman Haworth
Robert Robinson
Archer J. P. Martin
Richard L. M. Synge
Cyril Hinshelwood
Alexander Todd
Frederick Sanger

Table 4 (*continued*)

Biological Scientists

Ronald Ross
Archibald V. Hill
Frederick Hopkins
Charles Sherrington
Edgar Adrian
Henry Dale
Howard Florey
Alexander Fleming
Ernst Chain
Hans Krebs

Total 37 Nobelists

How Britain emerged as a scientific hegemon requires a focus on Cambridge, where the university produced more major scientific discoveries in this period than any university anywhere.[7] Of course, Cambridge's strength in science extended over several hundred years, with its former students including Francis Bacon, Isaac Newton, and Charles Darwin. However, the catalyst for Cambridge's modern scientific prominence was the British realization in the latter part of the nineteenth century that Germany was rapidly becoming a great power, and that among the most important factors contributing to this status was the German education system, particularly its research universities. In response to this, the UK government began to spur the universities at Oxford and Cambridge to place greater emphasis on scientific research. At Cambridge the physics of James Clerk Maxwell and the founding of the Cavendish Laboratory in 1871, with Maxwell as its first director, expressed this new emphasis.

The Cavendish lab was the nucleus of Cambridge physics in the late nineteenth and early twentieth centuries. During his life, Maxwell was recognized as one of the world's leading scientists, and today many would list him among the fifty most important scientists of all time.[8] Maxwell's successor was Lord Rayleigh (John William Strutt), who became one of the most renowned physicists of the late nineteenth century and was the fourth recipient of the Nobel Prize in physics. Rayleigh was followed as director of the Cavendish by several other outstanding physicists, each of them in due course a Nobel laureate: J. J. Thomson, Ernest Rutherford, Lawrence Bragg, and Neville Mott—a world record for a single laboratory.[9]

Yet the directors' Nobel Prizes represent only a small part of the extraordinary achievements of scientists working at the Cavendish. From the turn of the century to 1937 (the death of Rutherford), the following individuals did all or part of their work at the Cavendish for which they received a Nobel Prize: Lawrence Bragg, Francis Aston, C.T.R. Wilson, Owen Richardson, James Chadwick, George Thomson, Patrick Blackett, John Cockcroft, Ernest Walton, and Pyotr Kapitza. Between the beginning of Bragg's tenure as director in 1938 and departure from Cambridge in 1953, the following did all or part of the work for which they were awarded a Nobel Prize at the Cavendish: Francis Crick, James D. Watson, Max Perutz, John Kendrew, and Martin Ryle. In addition, Paul Dirac was awarded a Nobel Prize for work in physics he conducted at Cambridge. Table 5 lists all the scientists who did some or all of their Nobel prize-winning work at the Cavendish Laboratory prior to 1960.

Table 5. Nobel Laureates Who Did Some or All of Their Work at the Cavendish Laboratory, Cambridge, Prior to 1960

Lord Rayleigh
J. J. Thomson
Ernest Rutherford
Lawrence Bragg
Francis Aston
Charles Wilson
Owen Richardson
James Chadwick
George Thomson
Patrick Blackett
John Cockcroft
Ernest Walton
Francis Crick
James D. Watson
Max Perutz
John Kendrew
Martin Ryle
Pyotr Kapitza

Numerous other Cambridge-based scientists of considerable distinction were part of the greater Cavendish physics community. These included Rutherford's son-in-law, Ralph Fowler, whose research expertise included pure mathematics, statistical mathematics, astrophysics, quantum theory, thermodynamics, and fundamental theories of semiconductors. There was also Arthur Eddington, one of the major astrophysicists of the twentieth century, and J. D. Bernal, one of the most influential crystallographers of the first half of the twentieth century. Linus Pauling referred to Bernal as more creative than "any other living man," and "one of the greatest intellectuals of the twentieth century."[10]

No department has ever had so many distinguished scientists as the Cavendish Laboratory. Indeed this single department has received more Nobel Prizes for work actually done at the Cavendish than all the French and Italian science Nobel laureates combined. Yet the distinction of the Cavendish was only the tip of the iceberg of the greatness of British science in the first half of the twentieth century. As a whole, British science was clearly the global scientific hegemon during the first half of the twentieth century.

With the decline of the British Empire during and after the Second World War, Britain's power as a scientific hegemon also diminished. However, the British case in science is very different from that of the French after the decline of its political and military hegemony in the nineteenth century. In the United Kingdom, science continued to be quite strong, unlike in France, probably because the country's political system remained relatively democratic and not highly centralized. British science continued to be highly creative for the rest of the twentieth century. More than two dozen Nobel Prizes were awarded to British scientists up to 2000 for work begun after 1950—more than in any other country after the United States. While this is clearly only one indicator of scientific creativity, it is undoubtedly significant.

American hegemony and scenarios for the future

By the end of the Second World War, the United States had picked up the baton in science and still holds it. The United States emerged from the war as the world's dominant economic, political, and military power, which facilitated its dominance in scientific creativity. Since then, American scientists have received more than half of the most prestigious awards in science, such as the Nobel, Lasker, Horwitz and Crafoord prizes—major indicators of high levels of scientific creativity. For many years US researchers have dominated scientific journals, accounting for approximately thirty percent of all published papers and more than fifty percent of the top one percent of most cited papers. The United States has also attracted large numbers of young scientists for advanced training, recalling the migration of thousands of Americans to German universities and the flow to Britain of scientists from the British Empire in the later nineteenth century and after; and English has remained the world's dominant scientific language.

But history suggests that the United States has no cause for complacency about its future levels of creativity. Patterns in the rise and decline of scientific hegemons suggest that the United States could eventually look back on the early twenty-first century as the peak of its scientific dominance. Each former giant of scientific creativity emerged when the society's economy became extraordinarily robust by world standards. As the French, German and British economies declined, so did their science systems. 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 center would shift.

What is the state of scientific creativity in the United States?

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.

Meantime, the scale of science has changed in many areas of science, raising interesting questions about creativity at the level of the individual. The United States has led the way in the emergence of 'Big Science' (e.g., the Manhattan Project, the Jet Propulsion Lab, the Lawrence Livermore, Argonne, and Brookhaven National Laboratories). Indeed, in many fields there has been a major shift from individual to team 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 scientific papers than individuals, leading to a boom in scientific publishing. In recent decades, the average 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. However, as scientific creativity is achieved primarily by individuals, measures of performance at the collective level pose difficult problems for assessing levels of creativity. This leads us back to the first paragraph of this essay: what is the right level of analysis for measuring creativity?

In some fields, the transformation towards Big Science has built in irreversible constraints for organizing scientific research. During the past half-century, research universities, research institutes, and research-oriented pharmaceutical companies have dramatically increased in number. Many universities, especially in the United States, have become increasingly bureaucratic and fragmented, with numerous huge departments, organized like silos, impeding communication across fields.

The number of postdocs, research assistants, and technicians 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, with universities glad to have the staff as long as they can bring in large research grants and pay substantial institutional overhead costs. However, granting agencies and universities, realizing that this kind of structure has become dysfunctional, have made efforts to reduce the number of managerial levels and to develop matrix-type teams to minimize organizational rigidities. But organizational inertia hampers these reform efforts.

The ballooning of publications has meant that universities, funding agencies and reviewers have less time to evaluate scientific output, i.e., publications, carefully, and have come to rely more and more on quantitative measures based on citation statistics to assess creativity. The creativity of individual scientists is measured more and more by the number of papers on which the scientist is listed as a participant in the research and on how much research funding the scientist has generated. At the same time, the increasing commercialization of science has tended to emphasize short-term scientific horizons. All these trends pose serious problems for the future creativity of US science. As funding agencies and leaders in the scientific community increase the incentives to commercialize science, the system risks losing its flexibility and diminishes its capacity to make major, fundamental discoveries that may become the basis for new technologies some forty or fifty years hence. For, as is well known, new knowledge (e.g., major discoveries) often appears in an unanticipated and unplanned process with unpredictable consequences.

Is it possible to alter the dynamics?

Our research on more than 300 major discoveries in basic biomedical science in Britain, France, Germany, and the United States since 1900 demonstrates that a large percentage of the highest scientific creativity occurred in organizational contexts having the characteristics described in table 6.[11] The few organizations where major breakthroughs occurred again and again were relatively small; they had high autonomy, flexibility, and the capacity to adapt rapidly to the fast pace of change in the global environment of science. Such organizations tended to have moderately high levels of scientific diversity and internal structures that facilitated the communication and integration of ideas across diverse scientific fields. Most of these organizations had scientific leaders with a keen scientific vision of the direction in which new fields in science were heading, a strategy for recruiting scientists capable of moving a research agenda in that direction, and the ability to nurture young scientists while socializing them to accept the highest standards of scientific excellence (see table 6).

Table 6. Characteristics of Organizational Contexts Facilitating the Making of Major Discoveries*

What qualities of an organization facilitate making major discoveries?
1. Organizational leadership with (a) capacity to understand the direction in which scientific research was moving, (b) strategic vision for integrating diverse areas and providing focused research, (c) ability to secure funding for these activities, (d) capacity to recruit individuals who could confront important scientific problems that could be solved, and (e) capacity to provide rigorous criticism in a nurturing environment.
2. Moderately high scientific diversity—meaning organizational contexts (e.g., entire organizations, departments) with a variety of biological disciplines, medical specialties and sub-specialties, and numerous people in the biological sciences with research experience in different disciplines and/or paradigms.
3. Communication and social integration in the organization—meaning scientists from different scientific fields come together with frequent and intense interaction in collective activities such as: (a) joint publication, (b) journal clubs and seminars, (c) team teaching, (d) meals and other informal activities.
4. Recruitment—capacity to recruit individual scientists who internalized a moderately high degree of scientific diversity.
5. Organizational autonomy and organizational flexibility—the degree to which the organizational context of research was relatively independent of its institutional environment, and organizational flexibility was the ability of the organizational context to shift rapidly from one area of science to another. For organizational autonomy and flexibility, the organizational context had to be loosely coupled to its organizational environment. If the organizational context were a sub-part of a larger organization, it could attain flexibility and autonomy only if it were loosely coupled both to the larger organization and the institutional environment.

* These characteristics were derived from in-depth analysis of the organizational contexts in which major discoveries either occurred or did not occur throughout the twentieth century.

Dozens of scientists who made significant advances did so in an organizational context with fewer than fifty full-time researchers. In the recent past, some of the most creative work in basic biomedical science occurred in relatively small centers such as 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, United Kingdom, and various Max-Planck Institutes in Germany.[12] Since 1998 several Nobel prizes have been awarded to scientists for work done in relatively small US institutions: 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).

Table 7 presents the characteristics that place constraints on the ability of organizations to make major discoveries.

Table 7. Characteristics of Organizational Contexts Constraining the Making of Major Discoveries*

What qualities of organizations hamper the making of major discoveries?

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1. High differentiation—organizations were highly differentiated internally when they had sharp boundaries among subunits such as basic biomedical departments and other subunits such as departments, divisions, or colleges, including with regard to delegation of recruitment and responsibility for extramural funding.

2. Hierarchical authority—organizations were very hierarchical when they had centralized decision-making about research programs, number of personnel, work conditions, and/or budgetary matters.

3. Bureaucratic coordination—high standardization of rules and procedures.

4. Hyperdiversity—diversity to the degree that there could not be effective communication among actors in different fields of science or even in similar fields.

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* These characteristics were derived from in-depth analysis of the organizational contexts in which major discoveries either occurred or did not occur throughout the twentieth century.

Most large universities in the United States, France, Germany, and the United Kingdom, have tended to show the characteristics described in table 7: differentiation into large numbers of scientific disciplines, less communication across scientific disciplines compared to that in small organizations, and less organizational autonomy and flexibility to adapt to the fast pace of scientific change.

Why would organizations able to facilitate communication across diverse fields and, thus, to integrate scientific diversity, have an advantage in making major discoveries over those which have a lower capacity for such communication and integration? In our study of major discoveries, every single one reflected a great deal of scientific diversity. Of course, very good science occurs in organizational environments highly specialized within a very narrow field where there is little connection across disciplines and sub-specialties. But the science produced in such narrow and specialized environments tends to reflect insufficient diversity to be recognized as a major discovery by the scientific community, with its vast array of different disciplines. Nonetheless, major breakthroughs did occur in the type of organizational context described in table 7—but only when the individual laboratory making the discovery was structured quite differently from most laboratories in that type of organizational context. In other words, the lab was headed by a scientist operating in an organizational environment which generally would not be expected to have a major discovery.[13]

If the past is a guide for the future, America's science system could enhance its performance—particularly in basic biomedical science, but in other fields as well—by creating several dozen small research organizations in interdisciplinary domains or in emerging fields, modeled along the lines of the organizations mentioned above. In recent years, there have been several such efforts, for instance, the Howard Hughes Medical Institute's Janelia Farm in Virginia, the Santa Fe Institute in New Mexico, the Institute Para Limes in Warnsveld, the Netherlands, and the new Institute for Quantum Optics and Quantum Information in Vienna. Each of these small institutes has strong links with other organizations and a continuing group of visiting scientists. What is envisioned here are small institutes, each the hub in a network: a variation on the practice a few decades ago of the Woods Hole Oceanographic Institution, Cold Spring Harbor Laboratory, or the Salk Institute with its nonresident fellows consisting of a stable of future Nobel laureates (e.g., Francis Crick, Torsten Wiesel, David Hubel, Jacques Monod, and Gerald Edelman).

Perspectives on the future

The decline of the US economy relative to the rest of the world is facilitating the strengthening of science elsewhere. An evolving multi-polar world economy is leading to multiple centers 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.[14]

A remarkable change has been the emergence of China as an important power in science. 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, according to Thomson Reuters ISI; and by 2007 it was second. Between 1994 and 2008, the number of natural sciences and engineering doctoral degrees awarded in China increased tenfold, so that by 2007 China had surpassed the United States for the largest number awarded in the world. Moreover, in recent years more and more senior expatriate scientists have been returning to China. Of course, such indicators tell us little about highly creative achievement at the level of the individual—but they do have implications about the future trends for creativity in China.

As we reflect on the future of US scientific creativity, there are several possible scenarios to consider. One possibility is that the American system will continue to perform extraordinarily well with a continued exponential growth in the number of research articles and journals.

A second scenario is similar to what is occurring in the world of business. Just as business firms are becoming increasingly globalized, the organization of science will also become more global in nature, with scientists having greater mobility, moving back and forth among labs in Germany, the United Kingdom, Singapore, China, Australia, India, the United States, Scandinavia, etc. While certain geographical locations will remain stronger than others, there will be increasing convergence in the structure of research organizations, labs, and their performance across major regions of the world.

A third scenario is that commercialization of science will increasingly take place, to the long-term detriment of fundamental major discoveries as research organizations become excessively concerned with pecuniary gain, with short-term scientific horizons. But the successful functioning of an advanced industrial society depends on an abundant flow of fundamental basic knowledge. Such fundamental knowledge has unintended consequences. As suggested above, it often takes three or four decades, or even longer, before a fundamental discovery has an economic payoff. The X-ray crystallographic work of William and Lawrence Bragg, for which they were awarded a Nobel Prize in 1915, which was followed by much more work in crystallography by others, is only now being used for advances in drug discovery. Similarly, the path-breaking work of Oswald Avery in 1944 about genes and DNA and the discovery of the structure of DNA by Crick and Watson in the early 1950s are now—a half-century later—having significant consequences for the biotech industry. Indeed, the work of the three Nobel Prize winners in physiology or medicine announced in 2007 was very dependent on the work of Avery, Crick and Watson more than a half century ago.

The fourth scenario is the one suggested above, in which scientists make major discoveries in relatively small organizational settings. This is not to suggest that there is only one type of organization suitable for fundamental discoveries. But we do need to be mindful that excellence in science can still occur on a very small scale. This is true not only in the basic biomedical sciences, but also in the world of physics, which some tend to think can flourish only as Big Science. Even in physics excellent science is still occurring within small groups, often consisting of only one or two senior investigators plus two or three young assistants. Speaking of his own field, the physicist Per Bak argued some years ago that the dominance of large-scale physics projects has ended.[15] Consider some of the most recent Nobel Prize winners in physics whose work was done in relatively small settings: Klaus von Klitzing (1985) for his work on the quantum Hall effect in semiconductors; Alexander Muller and Georg Bednorz (1987) in Zurich for their work on superconductivity in ceramic materials; Gerd Binnig and Heinrich Rohrer (1986) of the IBM Labs in Zurich for their design of the scanning tunneling microscope; and Pierre-Gilles de Gennes (1991) of the Collège de France for his discoveries in liquid crystals and polymers—followed by a number of other Nobel Prizes toward the end of the twentieth century also involving small-scale science. But it has not been just Nobel laureates in physics who have been able to do excellent work on a low budget. For example, at the relatively small Rockefeller University, two very creative physicists, Mitchell Feigenbaum and Albert Libchaber, have done much of their most creative work alone in fields related to chaos theory and small-scale fluid experiments.

There is no certainty that the US system of science is in decline. But in our judgment, for the system to continue to make fundamental discoveries and flourish relative to other major centers of science, it must have organizations with a high degree of flexibility and autonomy, in which scientists can have intense interactions with one another across diverse fields. American society has the potential to develop and maintain such organizational settings. If funding agencies and leaders in the scientific community do not recognize the necessity of placing limits on the commercialization of science with its associated large-scale research environments, the system risks losing its flexibility and its capacity to make fundamental new discoveries without regard to their immediate applicability.

A number of studies sponsored by the National Science Foundation and other funding agencies have demonstrated that more than half of the major technological innovations in the twentieth century resulted from fundamental science, i.e, science conducted without regard for its usefulness. While no one knows what the proper balance should be between fundamental research and applied research, we should reflect on the possibility that without a strong commitment to fundamental research, American society may have a dearth of fundamental new knowledge to draw upon for new applications some forty or fifty years down the road.

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Endnotes

1 Guerlac, 1964; Sinding, 1999.
2 Weart, 1979: 26.
3 Shinn, 1979.
4 Ben-David, 1960; Nye, 1983 and 1984.
5 Beyerchen, 1977.
6 Born, 1978; Nachmansohn, 1979.
7 Hollingsworth and Hollingsworth, forthcoming.
8 Mitchell, 2009: 43.
9 Crowther, 1974; Harman and Mitton, 2002.
10 Brown, 2005: 473, 485.
11 Hollingsworth and Hollingsworth, 2011.
12 Hollingsworth, 2004.
13 Hollingsworth, 2006; 2007.
14 Hollingsworth, Müller and Hollingsworth, 2008.
15 Bak, 1996.

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