eu.esis journal

eu.esis
Association for the Promotion of the Scientific Endeavour

Volume 2
Winter 2012

journal homepage
www.euresisjournal.org

Factors associated with scientific creativity

Rogers Hollingsworth

University of Wisconsin, 455 North Park Street, Madison WI 53706-1483, USA
hollingsjr@aol.com

Abstract

The study of creativity in science, mathematics, art, and literature is enormously complex. What is defined as creativity varies across fields, as well as across societies and time within specific societies. Creativity at the level of individuals is influenced by personality traits and facilitated or hindered by the social environment. To illustrate these points, this paper focuses primarily on a single but broad area of science: the basic biomedical sciences, which include many fields of biology and chemistry. The paper also makes soft comparisons with other areas of creativity. The analysis focuses on creativity in Britain, France, Germany, and the United States from the late nineteenth century to the present. The main concern of the paper is to advance understanding of personal, organizational, institutional, and global factors which facilitated individuals making major discoveries in these four countries and across time.

1. Introduction

On the subject of creativity in the basic biological sciences, the paper addresses three basic questions:

1 What were some of the traits at the level of individuals which influenced their creativity and the making of major discoveries?

2 How did institutional and organizational factors facilitate or hinder creativity and the making of major discoveries?

3 How did the global economic environment of the four countries in discussion here (Britain, France, Germany and the United States) facilitate or hamper creativity and the making of major discoveries?

The paper addresses only a small part of a much larger research project in which I have been involved for some years. Some of the materials herein have been presented in quite different forms elsewhere, while other sections of the paper are presented for the first time [1]. The types of data used for this paper as well as my larger research agenda are briefly discussed in appendix II.

At a conceptual level, a major discovery or "breakthrough" in the basic biomedical sciences is a finding or process, often preceded by numerous small advances, which leads to a new way of thinking about a problem. This new way of thinking is highly useful to numerous scientists in addressing problems in diverse fields of science. Historically, a major discovery in biomedical science was a radical or new idea, the development of a new methodology, or a new instrument or invention. It usually did not occur all at once, but involved a process of investigation taking place over a substantial period of time and required a great deal of tacit and/or local knowledge. I have chosen to depend on the scientific community to operationalize this definition, counting as major discoveries those bodies of research that met at least one of the ten criteria listed below in appendix II, part 1.

Individual creativity is influenced by factors at multiple levels of society: psychological traits of individuals, research organizations, and the institutional and economic environments in which scientists work (see figure 1). Thus, the study of creativity in this paper requires a multi-level form of analysis.

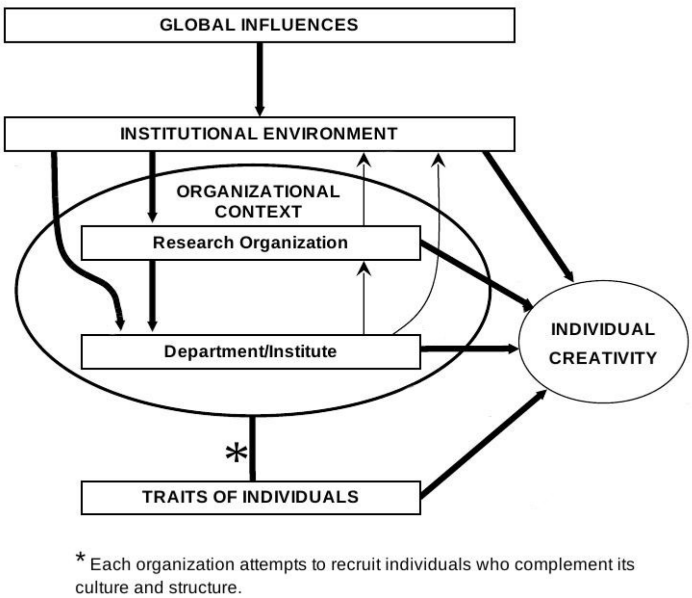


Figure 1: Factors at multiple levels influencing individual creativity in basic biomedical sciences.

2. Traits Facilitating Creativity of Individuals

There are numerous psychological factors associated with creativity of individuals. Here the discussion focuses on only one trait—high cognitive complexity—which facilitates creativity associated with the making of major discoveries in basic biomedical sciences. The paper explores two processes particularly notable in increasing the cognitive complexity of basic biomedical scientists: internalization of multiple cultures and strong commitment to non-scientific avocations. It argues that distinguished scientific achievement resulted from the internalization of scientific diversity, but it was cognitive complexity which facilitated scientific diversity, high scientific achievement, and high levels of creativity.

Implicit in this paper is the argument that it was the internalization of multiple cultures and/or strong commitment to non-scientific avocations which led individuals to have high cognitive complexity, scientific diversity, and creativity. Individuals with high cognitive complexity had the capacity to observe and understand in novel ways the relationships among complex phenomena, the capacity to observe and understand relationships among disparate fields of knowledge. And it was that capacity which greatly increased their scientific creativity and enhanced their potential for making a major discovery. Every one of the more than three hundred twenty-four discoveries in my research involved crossing or integrating parts of several scientific fields. The research has revealed that a major indicator of high cognitive complexity was the degree to which scientists cognitively internalized scientific diversity. Indeed, a necessary condition for making a major discovery was that the senior scientist associated with the breakthrough internalized a high level of cognitive complexity. For this reason, an intriguing and important problem is to understand why scientists have varied in having high levels of cognitive complexity. Of course, not all scientists with high cognitive complexity made a major discovery.

Individuals who had high cognitive complexity tended to be more tolerant of ambiguity, more comfortable with new and contradictory findings. Moreover, such individuals had a greater ability to observe the world in terms of grey rather than simply in terms of black and white. There was also a strong emotional component to cognitive complexity: scientists with high cognitive complexity very much enjoyed learning new things. Moving into new areas was like playing. They tended to be intuitive and had a high degree of spontaneity in their thinking, to be individuals who enjoyed exploring uncertainty and engaging in high-risk research rather than working incrementally in areas already well developed.

There were numerous pathways by which one might internalize scientific diversity. For many scientists, a common pathway to high cognitive complexity was their internalization of multiple cultures, often based on ethnicity, nationality, and/or religion. To acquire multiple cultural identities, it was not sufficient to live in a world where one was simply exposed to multiple cultures. Rather one had to be sufficiently socialized into multiple cultures so that one actually internalized the norms, habits, and conventions of more than one culture. Such an individual then literally had the capacity to live intuitively in multiple worlds simultaneously. The argument here is that such an individual had the ability to observe the world in more complex terms and the potential to be more innovative than those who internalized less cultural diversity.

There is an extensive literature pointing to the high achievements of German-Jewish scientists in the first third of the twentieth century, achievements quite out of proportion to the Jewish fraction of the German population. A common explanation has been the emphasis which Jewish families placed on formal learning. While this is part of the explanation, a more important factor was their internalization of multiple cultures which resulted in high cognitive complexity. There were numerous non-Jewish scientists of high distinction who also internalized multiple cultures: some who were part Polish and part French, some had one parent who was Catholic and another Protestant, some had one parent who was French and another North African, some who internalized Latin American and British cultures, and so forth. Because such individuals lived in intimate association with multiple worlds, they tended to have weak identities with each, and for this reason they could more clearly perceive the world with a certain detachment, to have a higher level of cognitive complexity, and to have the potential to develop novel or creative views of the world.

The scientists in the population I analyzed who internalized multiple cultures tended to be both insiders and outsiders, and it was this capacity to live in more than one world simultaneously that was the key to having high cognitive complexity and creativity. When they attended universities, it was almost second nature to cross from one field into another, to be both an insider and outsider. Just as in their personal lives they internalized multiple cultures, in their scientific lives they also internalized scientific diversity. And it is no accident that in an age of specialization, the discoveries by these scientists reflected a great deal of scientific diversity. One of their key traits was the capacity to see and understand relations among multiple fields. Every one of the scientists who made major discoveries in my study demonstrated considerable capacity to internalize scientific diversity: this was a vital key to their creativity.

As suggested above, many observers have long been aware that some of the most renowned scientists of the twentieth century were Jewish. Within my population of scientists who internalized multiple cultures and who made major discoveries in the basic biomedical sciences[1] were such well-known Jewish scientists as the following: Gerald Edelman, Fritz Haber, Roald Hoffmann, Francois Jacob, Eric Kandel, Aaron Klug, Hans Krebs, Karl Landsteiner, Rita Levi-Montalcini, Jacques Loeb, Andre Lwoff, Elie Metchnikoff, Otto Meyerhoff, Max Perutz, and Otto Warburg. During my research, I became increasingly interested in those who internalized multiple cultures so I could better understand some of the determinants of high cognitive complexity and creativity. I first focused on Jews who made major discoveries in basic biomedical science, as in my interviews and other investigations it became quite obvious that many of these were individuals who not only had high cognitive complexity but also internalized multiple cultures. Interestingly, the number of Jews in the population proved to be far greater than my colleagues and I originally suspected.

1 Jewish Winners of the Lasker Award in Basic Medical Research," http://www.jinfo.org/Biology_Lasker_Basic.html. (accessed 7 November 2011).

In a very strict sense, there is no single definition of a Jew. Some had an identity as being Jewish even if they were not Jewish in a religious sense, or did not associate with others who were Jewish. Indeed, some disguised their Jewish origins and married non-Jewish spouses. Some were extraordinarily secular or even atheist. In my research, I include high-achieving scientists if their Jewish background—however defined—contributed to their (1) having some awareness of being Jewish and (2) contributed to their internalization of multiple cultures and having high cognitive complexity.

How a Jewish background worked out was very complex and varied from person to person and from society to society. Many were marginal to the society in which they grew up. Some like Nobel laureate[2] Gertrude Elion were essentially "multiple outsiders." Her father had arrived in the United States from Lithuania and had descended from a line of rabbis who have been traced through synagogue records to the year seven hundred. Her mother had emigrated from a part of Russia that is now part of Poland and her grandfather had been a rabbi. Gertrude's maternal grandfather had the greatest influence on her. He was a learned biblical scholar who was fluent in several languages, and for years Gertrude and her grandfather spoke Yiddish together. But Gertrude as a young girl realized that she wanted to be a scientist—a man's profession. Hence, she not only internalized the culture of being Jewish and American, but also being a woman in an occupation dominated by men (see interview with Elion).

Rosalyn Yalow was another Nobel laureate whose early life was being both insider and outsider. Her Jewish parents were immigrants to the United States who had little formal education, but they strongly encouraged her education. Hence during Yalow's early years, she tended to live in two separate worlds: one in which she received much encouragement from her uneducated immigrant parents and another in the public schools of the South Bronx. Later, she became very interested in physics, a male-dominated world. Again, she was an outsider. Fortunately for her, when she began graduate work during the Second World War there were not enough male graduate students to be research and teaching assistants. As a result, she was given a stipend by the Physics Department of the University of Illinois. Subsequently, she began to work with a group of physicians in the Bronx Veterans Administration hospital, but as a physicist she was once more an outsider. It was as a result of this dual role of being both insider and outsider that she was able to establish bridges between the world of physics and medicine and to be one of the few scientists in the developing field of nuclear medicine.

As the sociologist Robert Park [2] observed many years ago, the "outsider" is often a personality type which emerges where different cultures come into existence, and such an individual often assumes both the role of the cosmopolitan and the stranger. Because such

2 Jewish Nobel Prize Winners," http://www.jinfo.org/Nobel_Prizes.html. (accessed 7 November 2011).

an individual internalizes multiple cultures, he/she has the potential to develop a wider horizon, a keener intelligence, a more detached and rational viewpoint—the ingredients of a creative person. Somewhat earlier, the German sociologist Georg Simmel [3] developed similar ideas about creativity. The psychologist Mihaly Csikszentmihalyi, a leading writer on creativity, has reminded us that many highly creative individuals felt marginalized in their lives. Some experienced the life of the marginal individual because of their early success. Many scientists overcompensated for their marginalization with a relentless drive to achieve success, determination based on sacrifice and discipline, but at the same time a fascination with constant learning about novel things.

Many individuals emerged from a multicultural world but never internalized in a deep sense the cultural diversity of their environment. All other things being equal, the greater the cultural diversity within a social space, the greater the likelihood that an individual will internalize multiple cultures and have potential to be highly innovative. However, there are many qualifications which must be made to such a generalization. The more structural and cultural barriers among those of different cultural backgrounds and the less the access to leading centers of learning, the lower the likelihood that individuals in a multicultural society will internalize cultural diversity. In multicultural societies, there is variation in the degree to which individuals will internalize multiple cultures. Poland, Germany, and Austria in the first third of the twentieth century were multicultural societies, but Polish Jews faced greater cultural and structural obstacles to scientific institutions than German and Austrian Jews. Even though anti-Semitism existed in all three societies, it was most intense in Poland, and partly for that reason, Polish Jews were less able to internalize cultural diversity and to be as innovative as Jews in Austria and Germany at the same time. This difference explains in part differences among Jewish populations in creativity in these three countries in the first third of the twentieth century.

Thus far, the argument has been that cognitive complexity due to the internalization of multiple identities tends to enhance scientific diversity and scientific achievement. Creativity is further enhanced in those who already internalize considerable cultural diversity by engaging in mentally intensive avocations. On the other hand, many scientists who did not internalize multiple cultures added to their creativity by engaging in mentally intensive avocations which on the surface did not appear to be related to their scientific work. On the basis of numerous in-depth interviews and from my study of biographical and archival materials, many scientists have made it abundantly clear that their avocations enriched the complexity of their minds and that many of their scientific insights were derived by engaging in what often appeared to be non-scientific activities. The Root-Bernsteins [4,5] have presented data and theoretical arguments demonstrating that skills associated with artistic and humanistic expression have positive effects for scientific creativity. They contend that scientific accomplishments are enhanced by the capacity to be high achieving in multiple fields—scientific as well as non-scientific—and by having the opportunity and ability to make use in science of skills, insights, ideas, analogies, and metaphors derived from non-scientific fields. Many scientists have commented about the intuitive and non-logical factors in the act of discovery. Others emphasized how the arts and humanities had the potential to stimulate their senses of hearing, seeing, smelling—enhancing the capacity to know and feel things. Einstein frequently observed that his theory of relativity occurred by intuition, but music was "the driving force behind the intuition ... my new discovery is the result of musical perception" [6]. Einstein's son observed of his father that "Whenever he had come to the end of the road or into a difficult situation in his work, he would take refuge in music, and that would usually resolve all his difficulties" [7; 106]. Root-Bernstein goes so far as to argue that "no one with monomaniacal interests or limited to a single talent or skill can [...] be creative, since nothing novel or worthy can emerge without making surprising links between things [....] To create is to combine, to connect, to analogize, to link, and to transform." [8; 66]

If fundamental discoveries are derived from experiencing unexpected connections from disparate fields and if discovery often has a strong emotional and intuitive quality to it, we should not be surprised that many of the scientists in my population who were recognized for making major discoveries were also individuals who were quite accomplished performers in areas other than the scientific field for which they were renowned. There is indeed a very rich body of data revealing that highly recognized scientists in many fields were quite talented as writers, musicians, painters, sculptors, novelists, essayists, philosophers, and historians. A number were also engaged in political activities—both closely and distantly related to their scientific activities. In my analysis of scientists who made major discoveries there were many who were also quite accomplished in artistic and humanistic activities.

Numerous renowned twentieth-century scientists had avocations in different fields which undoubtedly enhanced their cognitive complexity/creativity. My data is still incomplete about the avocations of a number of scientists in my population for making major discoveries. I have yet to interview a number of scientists receiving awards during the last ten years. Nor have I had an opportunity to study the archives or personal correspondence of all scientists receiving awards covering the entire scope of the study. Indeed, many such documents are not yet available for examination by anyone.

Table 1 demonstrates how some of the world's most creative physical, chemical, and biological scientists in the first Kaiser Wilhelm Institutes had a strong association between their science and various avocations. These institutes were located in Dahlem—a suburb of Berlin—in the second decade of the twentieth century. They were very small—having only a few scientists—but a number of these scientists received Nobel Prizes and had strong avocations which consumed considerable time.

Table 1

Characteristics of Individual Nobel Laureates and Scientists at Kaiser Wilhelm Institutes in Dahlem

Scientist	Nobel Prize	Cultural Diversity	Avocation
Albert Einstein	Nobel	Jewish	Musician, Political Activist, Writer, Sailing
James Franck	Nobel	Jewish	Musician, Political Activist
R. Goldschmidt	—	Jewish	Writer
Fritz Haber	Nobel	Jewish	Poet, Dramatist
Otto Hahn	Nobel	—	Musician, Poet, Architect
Hans Krebs	Nobel	Jewish	Musician, Writer
Lise Meitner	—	Jewish	Musician
Otto Meyerhof	Nobel	Jewish	Musician, Poet, Writer
Carl Neuberg	—	Jewish	
Max Planck	Nobel	—	Musician, Writer (KWG President, 1930–1935)
Michael Polanyi	—	Jewish	Philosophy, Writing
Axel Theorell	Nobel	—	Musician
Otto Warburg	Nobel	Jewish	Avid Horseman, Sailing (three major discoveries)
Richard Willstätter	Nobel	Jewish	Writer

The argument here is not that all scientists being highly creative made major discoveries. Rather, the main contention is that those who were highly creative—for whatever reason—tended to have qualitatively different styles of doing science than those who were less creative. The greater their cognitive complexity—whether as a result of internalizing multiple cultures and/or from participating in various artistic and humanistic fields—the greater the likelihood that they would be highly achieving, creative scientists.

For many scientists, pursuing activities as an artist, painter, musician, poet, etc., enhanced their skills in pattern formation and pattern recognition, skills that they could transfer back and forth between science and art. It was part of their ability to understand reality in more than one way. The great chemist Robert Woodward and many others marveled at how their activities as artists reinforced their abilities to recognize complex patterns in nature. Ronald Hoffmann, a Nobel laureate in chemistry—but also a poet—argues vigorously that scientists have no more "insight into the workings of nature than poets." Hoffmann's science describes nature with equations and chemical structures but he argues that his science is an incomplete description. By using poetic language to describe nature, he believes he has a richer understanding of the world. For him, the more different ways one can describe reality, the richer one's description and understanding. For Hoffmann [9,10] and many others, the roles of artist and scientist were mutually reinforcing. Nobel laureate Gerald Edelman (a renowned physical chemist, immunologist, cell biologist, and neuroscientist) reports that he derives many of his initial scientific insights from the ambiguities of life and nature revealed by poetry (see interviews with Edelman). He has great breadth about poetry, more than most poets I have encountered. In his autobiography, physicist Victor Weisskopf made the argument that artistic and scientific activities complement one another in the mind of the scientist, that both are needed in order to have a more complete understanding of the world.

3. Creativity in Science and Art

3.1. Similarities and Differences among Creative Individuals in the Arts and Sciences

Since some scientists were quite creative in both science and the arts, it is useful to emphasize some of the similarities and differences in the two domains. In both art and science, individuals must be well grounded in a particular domain. It is highly unlikely that individuals could make a creative advance without any prior training—that Beethoven, Brahms or Mahler could have written their symphonies or that Max Planck or Linus Pauling could have made their achievements without extensive and in-depth exposure to work which preceded them. In short, creative work must be rooted in a particular context—though creative individuals in both domains tend to be highly motivated, ambitious, hard working, and highly flexible—open to new ideas, willing to take risks that may result in severe criticism. Most such individuals have had a great deal of imagination and have intuitive insights.

Even though creative practitioners in both domains were grounded in a specific field, they also have had a wide range of knowledge of related fields. In both, there was a tension between their depth in a particular field and their range of knowledge of related fields. Another tension they shared was being both somewhat traditional in their thinking while also being rebellious. If they had been too innovative—far in advance of their contemporaries—they probably would not have been recognized for their contributions. Of course, there were exceptions. In modern science, one is immediately reminded of Gregor Mendel's famous work in genetics which was only recognized a generation after his famous paper and some years after his death. Likewise with the paper by Peyton Rous written in 1911 on cancer research, for which he received a Nobel Prize in 1966 (fifty-five years later), and Barbara McClintock's Nobel Prize (1983) for work completed more than three decades earlier. In economics, Ronald Coase's paper of 1937 was recognized with a Nobel award in 1991—fifty-four years later. Van Gogh's art was not recognized as very creative by his contemporaries.

To understand differences among artists and scientists, I draw insights from the philosopher of science Michael Polanyi [11,12], who emphasized two kinds of knowledge: tacit (personal) and explicit knowledge. Personal knowledge is that which all individuals internalize but which is difficult to communicate to others—the act of balancing and riding a bicycle, the aesthetic sense of having a religious experience, of perceiving a scene or an object as beautiful. Artists essentially communicate tacit or personal knowledge. Moreover, tacit or personal knowledge has a much longer life span than the explicit knowledge which scientists attempt to communicate. Shakespearian plays, the music of Bach, Handel, Mozart and Beethoven were much more intuitive, personal, and expressive than the work of scientists.

On the other hand, explicit knowledge is what scientists attempt to write and to communicate precisely to their colleagues. In some fields, scientists attempt to communicate explicitly with the language of mathematics. In many fields, the work of scientists—unlike that of artists—is expected to be refutable and/or verifiable by the standards of the day.

Unlike the creation of the artist, that of the scientist has a relatively short life. Long after the creative work of artists, audiences experience art by going to theaters, museums, and concerts. But the creative work of most scientists is soon forgotten as it is integrated into a larger body of knowledge, and the work thereafter is seldom read or cited by their successors—even if highly cited after three or four years of publication. Of course, the public discuss the work of Galileo, Newton, Darwin, Einstein, von Laue, Planck, Bohr, or Dirac but it is very rare that their work, or that of most who received Nobel Prizes, is cited or even read by subsequent generations—except by historians. In sum, the work of most high-achieving scientists is forgotten much more quickly than that by highly recognized artists.

3.2. Centers of High Creativity

A necessary condition for an abundance of high creativity in art and science is that the work be located in a society with considerable wealth by the standards of the day. At the societal level, there is a strong correlation between high economic performance and high creativity in both art and science. This was the case with various Greek city states, ancient Rome, and Florence in the fifteenth century, as well as in various societies over the past two hundred fifty years. Another necessary condition for high creativity is that the society have an abundance of talent, irrespective of whether in the arts or science. Individuals who wish to be creative tend to migrate to areas of wealth.

Within such societies, artistic creativity has generally been concentrated in only a few centers where people learned from others and had mentors who nurtured them. It was in these centers that there were gatekeepers who played an important role in deciding what was excellent and who was permitted to enter into the land of excellence. In the arts (e.g., theater, cinema, painting) Paris, Berlin, Vienna, London, New York, Hollywood at different moments exercised this function. It was in these centers where artists learned about their field, the constraints which influenced what was considered to be excellent. At the same time, large centers usually offered the opportunity for diverse views to be expressed, and it was in environments having considerable diversity that creativity was enhanced. Of course, in contrast to small societies (e.g., Norway, Sweden), large societies tend to offer more opportunities for diverse groups to gather in one or two cities. However, one can overstate the importance of large metropolitan environments as conditions for creative centers of art. Occasionally, small centers have provided the opportunity for intense interaction among individuals with diverse perspectives. However, small environments for intense interaction have usually lasted for only short periods of time—partly because they have tended to be poorly funded. A German example was the Bauhaus School consisting of some of the most creative artists of the last century: Walter Gropius, Lyonel Feinger, Mercel Breur, Wassily Kandinsky, Paul Klee, Ludwig Mies van der Rohe. An even smaller center in a more remote environment was the Black Mountain College in North Carolina in the 1930s. It too attracted a diverse group of artists, also some of the most creative artists of the last century: Josef Albers, John Cage, Merce Cunninham, Buckminster Fuller, Franz Kline, Willem de Kooning, Robert Rauschenberg, Cy Twombly. Later there were the Black Mountain Poets, an assembly of poets which was the center of avant-garde American poetry of the 1950s, many of whom later were among the most creative American poets of the twentieth century. Another exception to the idea of concentration has been in the crafts where highly creative individuals have often worked alone.

While most creative centers of art have been located in large urban areas, major centers of modern science have often been dispersed in multiple centers, not largely in one metropolitan area—such as eighteenth and nineteenth century French science which was centralized in Paris. In German science, Berlin was a major center, but so were Munich, Göttingen, Kiel, and Leipzig before the Nazi era. In Britain, there were Cambridge, Manchester, London, and Oxford. But it was in the much larger country of the United States where excellence in science has been most widely dispersed: Princeton in mathematics and physics; Caltech in astronomy, geological sciences, physics, chemistry, and biology; Harvard and MIT in physics, chemistry, and the biological sciences; Bell Labs, MIT, Berkeley, and Stanford in various fields of physics; Urbana in solid state physics; San Diego and Woods Hole in oceanography; Chicago, Harvard, and MIT in economics; clinical medicine in Baltimore, Bethesda, Boston, Chicago, Houston, Philadelphia, and Rochester, Minnesota—to mention but a few. Other major centers in the biological sciences have been the Salk Institute and the Scripps Research Institute—both in La Jolla, the University of Texas Southwestern Medical Center at Dallas, Cold Spring Harbor Laboratory on Long Island, and the University of California at San Francisco.

4. Institutional Factors Facilitating or Hampering Scientific Creativity

One of the factors influencing creativity at the level of the nation state is the institutional environment in which scientists conduct research. I code scientific institutional environments as ranging from weak to strong. Weak institutional environments exert only modest influence (1) on the appointment of scientific personnel of research organizations, (2) in determining whether a particular scientific discipline will exist in a research organization, (3) over the level of funding for research organizations, (4) in prescribing the level of training necessary for a scientific appointment (e.g., the habilitation), and (5) over scientific entrepreneurship (e.g., the norms of individualism that socialize young people to undertake high-risk research projects). Strong institutional environments are at the opposite end of the continuum on each of these characteristics. Weak institutional environments have tended to facilitate greater scientific creativity in a society than strong institutional environments (see figure 1).

France is an example of a country that tended to have a strong institutional environment throughout the twentieth century, while the United States had a relatively weak institutional environment. However, institutional environments of societies change over time, and changes in the institutional environment influence the potential of scientists within a society to be creative. There is a high degree of complementarity among the five concepts constituting institutional environments: when one is weakly developed, the others tend to be weakly developed and vice versa.

Strong institutional environments exert centralized control over the training of scientists and influence the kind of individuals who get recruited into research organizations. In France and Germany for example, there has historically been much more standardization in the credentials (e.g., training) required to be a university professor than has been the case in the United States. In Germany, the habilitation (a more advanced body of research than that for a doctorate degree) was generally completed between ages thirty-five and forty in biomedical science, and has generally been required for appointment as professor. Because the work for the habilitation must satisfy a senior professor and be accepted by a particular faculty in a university, the candidate has had much less autonomy to pursue completely independent lines of investigation at an early age than in the United States and Great Britain. The young American or British scientist, with much greater independence by age thirty, already has had more of an opportunity to pursue unorthodox or high-risk research. The consequence of this is that a somewhat higher percentage of young Americans and British engaged in basic biomedical research have often had greater opportunities to make highly novel discoveries—and to permit their potential for creativity to emerge.

As part of greater centralization of control, appointments to the rank of professor in German universities have long been made by the minister of education of the various federal states.

Although German universities have historically ranked several candidates for a particular professorship, the final choice is made by the minister. There have been numerous cases in which ministers have not honored the rankings of the university faculty. Moreover, it is the ministers who have decided whether faculties will be permitted new professorships, whether a university may have a new discipline. This kind of external bureaucratic process has tended to retard the ability of German universities to be highly flexible in adapting to the fast pace of change in the global world of science. In contrast, each university in the United States has had a high degree of autonomy to decide who will be a professor, what the criteria for appointment will be, and whether or not it will adopt a new discipline. Because of the different kind of institutional environment in the United States, American universities have had much greater flexibility to develop or adapt quickly to new trends in the world of science and technology.

Within an American university department, there have been many more professors than one would find in a university department on the other side of the Atlantic. The larger number of professors in American university departments has permitted more scientific diversity. This greater scientific diversity has been associated with major discoveries in biomedical science, especially when it has been combined with a social context which facilitates intense and frequent communication among scientists with diverse interests. And rich interaction among those with diverse views facilitates creativity.

Because there have been fewer professors in departments, German professors have tended to have many more varied responsibilities than their American counterparts, responsibilities which have constrained their potential for creative work in spite of their many talents. Because historically there have been relatively few professors in German university departments, the professors have had substantial teaching and administrative responsibilities, meaning they have had more modest opportunities to conduct research. Since there were fewer professors in each department, each professor's teaching has had to encompass a broader scope, and as a result, there has usually been less opportunity to relate teaching to research. All of these institutional constraints have hampered scientific flexibility and creativity in German universities.

Another effect of the institutional environment on research organizations relates to the strength of scientific disciplines. The very term "discipline" suggests order and control, and indeed academic disciplines attempt to regulate and shape the problems and methods which scientists confront on a daily basis. The stronger the academic discipline within universities, the less autonomy an individual scientist has to pursue radically new problems and to permit creative potential to emerge. In European countries where universities have had fewer professors in each department, disciplines have been much more fixed and less flexible. In the American context, where disciplinary-based departments have many professors, there have been greater opportunities for professors to deviate from the core of a discipline, even to join with colleagues from other disciplines to develop a new discipline and to be more creative. Although academic disciplines everywhere are institutional devices which restrict scientific autonomy and flexibility, disciplines tend to be more loosely ordered and less controlling in America than in Europe. Partly as a result, it has been more common for an American professor to hold an appointment in several disciplinary-based departments than in Europe. And the American professor who holds a professorship in more than one disciplinary-based department has had greater opportunity to internalize scientific diversity, a process associated with higher levels of creativity and the making of major discoveries in biomedical science.

Partly because academic disciplines have been less rigid in America, the Americans have had greater capacity to create new academic disciplines and to establish interdisciplinary institutes both within and outside universities.

In Germany, most of the Max-Planck Institutes for the biomedical sciences were built around a single discipline or scientific field. For example, historically there have been a Max Planck Institute for genetics, another for biochemistry, one for immunology, etc. Because most of these institutes functioned around single disciplines, they did not have the same degree of scientific diversity which one finds in some of the leading American and British research institutes in the basic biological sciences (Scripps, Salk, Laboratory for Molecular Biology, Hutchinson Cancer Research Center). However, there are many indicators that this has been changing in the Max-Planck Institutes since the collapse of the Berlin Wall. Today almost half the Max-Planck directors are either foreigners or Germans who spent considerable time abroad. Not surprisingly the quality of these institutes now rank among some of the world's major centers of research. It is significant that the Max-Planck Society is not a state organization—even though much of the funding of the institutes is derived from state sources. (In this connection, it should be observed that private American research universities receive much of their research funding from the federal government.)

In America a senior professor has had the opportunity for much more mobility not only from one research organization to another but also across disciplines within an organization than has been the case in most European societies. This is a consequence of the much weaker institutional governance environment in which American research organizations are embedded, and of the large number of American research organizations. The career path of the Harvard Nobel Laureate Walter Gilbert is hardly imaginable in France or Germany. Gilbert, with a doctorate in physics, began his teaching in physics and chemistry at Harvard, but eventually became a professor of biology and received a Nobel Prize in Chemistry (see interviews with Gilbert). Had his career taken place in Germany, with its expectation of the habilitation, he undoubtedly would have internalized much less scientific diversity, and it would have been much more difficult for him to do the kind of creative biological research resulting in his being recognized with a Nobel Prize in Chemistry. There are many other similar cases. For example, Gerald Edelman—a Nobel laureate—received his award for work in chemistry and immunology, but later turned to the field of cell biology, before moving on to neuroscience.

The system of organizing universities in Britain is more flexible than in Germany but somewhat less so than that in the United States. Thus, even though Francis Crick played an important role in shaping modern genetics, one of the reasons he was denied the professorship of genetics at the University of Cambridge was because he had been trained in physics and lacked a doctorate in genetics. Crick of course became one of the most important creative scientists in developing biology in the twentieth century. Max Perutz had a career in Britain that was hardly imaginable in his native Austria. He once observed that he was a chemist working on a biological problem in a physics institute (i.e., the Cavendish Lab at the University of Cambridge). He too became a Nobel laureate, but such an interdisciplinary career would hardly have been conceivable in either Germany or Austria (see interviews with Perutz, Crick, Klug, Brenner, and Edelman).

French research organizations are much more segmented than those of the other three countries. There are universities, medical schools, clinics, as well as INSERM and CNRS institutes (sometimes free standing and sometimes associated with other research organizations). Because the French system is highly segmented with each kind of organization having different types of goals, it has been much more difficult to move from one kind of organization to another in France than in the United States.

Funding mechanisms are important means by which the institutional environments may constrain the behavior of research organizations, the making of major discoveries, and creativity. Funding organizations generally have strong preferences about allocation of their research funds, thus placing some constraints on the creative potential of recipients. In most countries, scientists have had relatively few sources of funding. Heavily dependent on only a few organizations for their financing, researchers in Europe have generally had less autonomy than in the United States where there have been many different sources for financing biomedical research. A major exception in biomedical science has been the enormous generosity of the Wellcome Trust in London. The Trust has made it possible for a number of research organizations in Britain to be much more creative than they would otherwise have been. In the United States—apart from a few major governmental organizations for funding biomedical research—there have been literally thousands of private foundations, some very large—but with the exception of the Howard Hughes Medical Institute, none on the scale of the Wellcome Trust.

An important reason why there were so many major discoveries in the biological sciences at the University of Cambridge during the last century was because there were so numerous sources of funding for its scientists. Various colleges—especially Trinity—provided generous funding for junior and senior research fellows for periods between four and six years. The expectation was that the fellows would be engaged in full-time research. Various small groups of scientists received attractive funding from foundations, the Wellcome Trust, as well as from governmental research councils—but not through the competitive Request for Proposal (RFP) which have become so widespread in the United States. A number of other scientists became Professors of the Royal Society even before they made major discoveries—with no teaching duties and without having to submit a research proposal.

In the United States, the diverse pool of funding for biomedical research has meant that researchers and research organizations in the United States have had greater autonomy to pursue different research agenda than has been the case in virtually all European countries—and thus greater opportunity to launch radical innovations, to adapt quickly and creatively to changes in the scientific environment.

However, this perspective about the United States should not be overstated. Over time, most American scientists have become increasingly dependent on the National Science Foundation (NSF) and the National Institutes of Health (NIH) for their funding. As this has occurred, American scientists have had fewer opportunities to pursue high-risk research strategies. Increasingly, American scientists have had to adapt their research strategies to the preferences of study groups and program officers at NSF and NIH. Many have argued that this has begun to place constraints on the creativity of American scientists [13].

Having focused primarily on the institutional scientific environments of these four countries and how that impacted on their scientific performance, I now turn to a brief discussion about the relationship among institutional environments, the structure and culture of research organizations, major discoveries, and individual creativity.

5. The Impact of the Structure and Culture of Research Organizations on Individual Creativity

As suggested above, Great Britain's institutional environment was stronger and exercised greater control over research organizations than that in the United States but it was weaker than those of France and Germany. Significantly, British research organizations have performed extremely well in the making of major discoveries. As a result of having a weaker institutional environment, Great Britain—like the United States—historically also had considerable diversity in the type of research organizations making major discoveries, consisting of both public and private organizations. There were large federated private universities (the Universities of Cambridge and Oxford), large "public civic" universities (Birmingham, Liverpool, Manchester, Sheffield), large Scottish universities (Edinburgh and Glasgow), private institutes (Ross Institute, Glynn Research Council), the University of London (with colleges very different from those of Oxbridge), and governmentally funded institutes (the Agricultural Research Station at Rothamsted, the Medical Research Council's Laboratory of Molecular Biology, the National Institute of Medical Research). The amazing diversity of types of organizations in both the public and private sectors in a relatively small country is an indicator of the weak institutional environment in which British research organizations were historically embedded.

This kind of organizational diversity enhanced the performance of and potential for individual creativity in British research organizations. While the University of Cambridge had the second largest number of major discoveries in basic biomedical sciences during the twentieth century, the number of discoveries dropped dramatically at Cambridge during the last third of the twentieth century as the university became more centralized and the institutional environment's influence exercised over universities increased [14].

Both the increasing power of the institutional environment (e.g., the development and strengthening of academic disciplines, the standardization in governmental funding) and the difficulty research organizations had in obtaining funding for biomedical science contributed to these effects. In addition to the funding difficulties of British science, the performance of research organizations and individual creativity were impaired at the end of the twentieth century as a result of such programs as the Research Assessment Exercise in order to exercise greater centralized control by Whitehall over the funding of science. Nevertheless, normed by the size of the population, British research organizations performed extraordinarily well across the last century.

As implied above, there are numerous studies which indicate that Germany's research organizations have long been embedded in an institutional environment which exercised central control over many of their functions. Given my findings that strong institutional environments are not associated with many research organizations having major discoveries, it is not surprising that there have been few major discoveries in the basic biomedical sciences in Germany since the mid-1920s.

On the other hand, Germany was the country which first developed the model of a modern university. And it was in that environment that on a worldwide scale German Universities excelled in biomedical science in the late nineteenth and early twentieth centuries. During the latter two-thirds of the nineteenth century, the German style of organizing the biomedical and chemical sciences became the model which other countries aspired to duplicate.

By 1900, no other country had so many outstanding scientists and academic journals. Significantly, Germany was able to create such a distinguished system of science because of strong state authority with complementary strong rule systems. The German system of approximately twenty universities in the last two decades of the nineteenth century was highly innovative in developing the discipline of physiology, in advancing the fields of organic and biochemistry, as well as bacteriology and immunology. In the first quarter of the twentieth century, several German universities had multiple major discoveries in basic biomedical science; the performance of German universities was indeed impressive. Even so, the research quality of the German universities had begun to decline in the basic biological sciences by the first quarter of the century, a factor widely recognized in Germany, both within and without the universities. In response, the Germans created the Kaiser Wilhelm Institutes. Overall, German research in the biological sciences became increasingly frail and greatly weakened by World War I [15, 16].

Reflecting on the German system, it is important to note that it is possible for a centralized system to use its power to bring about major innovations—as the Germans did with their universities in the latter half of the nineteenth century. But once a centralized system of science has created a set of innovations and remains centralized, the system tends to become rigid and inflexible—less capable of adapting to changes in the global world of science.

Thus, it should not be surprising that by 1914, the German research system in the basic biological sciences had a lack of capacity to develop new universities and disciplines, as well as new chairs in older disciplines. The governance of German universities was widely shared with the state, as ministries of education decided whether or not there would be a new discipline, how many professors there would be in each discipline, and what they would teach and in what discipline they would do particular kinds of research. Of course, after the Second World War, a number of new German universities and research institutes did come into existence, but the German research organizations—relative to those in Britain and the United States—have long suffered from a lack of flexibility and autonomy in governance. This lack of flexibility and autonomy (for both universities and research institutes) has hampered the capacity of German research organizations, especially universities, to be very successful in making major discoveries since 1945. True, the Nazi era and the devastation brought about by World War II had an enormous destructive effect on German science, but the rigidity of the German system of knowledge production had set in before the 1930s. Thus, most of the German credits for major discoveries in the biological sciences had actually occurred before 1925, i.e., before the Nazi era which accelerated the decline in all disciplines. Because of their strong institutional environment, German universities have converged toward a common set of norms in their governance. And because they have tended to mimic one another in their structure and culture, there has been little diversity and less novelty in the processes of discovery than would have been the case had there been a greater variety of organizations. The German case is quite consistent with my data on other countries that adequate funding for science is not sufficient for organizations to make numerous major discoveries over time if the organizations are embedded in an institutional environment which severely limits their autonomy and flexibility.

The French case is much more straightforward. The number of research organizations with major discoveries has been very small relative to each of the other three countries. Among the four countries discussed herein, none historically has publicly praised scientists and their accomplishments more than has been the case in France. Christiane Sinding has reminded us that "the French Revolution replaced the king and the church with the worship of great men" [17]. Celebrations of "great scientists" and other "great notables" have become an important part of French culture. Among these four countries, none has been more parsimonious and lacking in foresight in providing scientists with the financial and organizational resources which they require.

Throughout the nineteenth and twentieth century, scientific facilities were extraordinarily underfunded and research was conducted in a very personalistic style. Some of France's greatest biomedical scientists—François Magendie, Claude Bernard, Charles-Édouard Brown-Séquard, Louis Pasteur, Pierre Curie and Marie Curie—often had to work under the most abominable conditions. It is a tribute to the French system of education, with its emphases on individual brilliance and creativity, that these scientists performed so well in underfunded research organizations. Even when the French government occasionally provided ample funding for laboratories, the method of governance was highly centralized. Over the years, French scientists in comparison with those in the other three countries, more often than not had to operate in crowded laboratories, had to rely on obsolete equipment, and periodically were subjected to the deleterious effects of inflation. It is true that over time there has been greater variation in the type of state run research organizations: universities, CNRS and INSERM research units, the College de France, hospitals, and the Musée de l'Histoire Naturelle (not a museum but a training and research center). But these separate organizations had little autonomy and flexibility and hence few major discoveries—resulting from an institutional environment for the nourishment of individual creativity.

Numerous accounts have described how the French university system was long embedded in a highly centralized Ministry of Education which determined salaries and promotions. Letters of evaluation were written largely by friends and mentors. There was an enormous amount of favoritism and organizational nepotism. Some of France's most distinguished scientists have often publicly made scathing criticisms of the system—its lack of funding, the mediocrity of its science, the perpetuation of antiquated disciplines and the reluctance to develop new ones, the incompetence of administrative personnel. The distinguished French biologist Ernst Boesiger observed that as late as 1974 France was "a kind of living fossil in the rejection of modern evolutionary theories," with approximately ninety-five percent of all biologists opposed to Darwinism [18]. Most French biologists from 1920 through the mid-1950s rejected much of the knowledge derived from the breakthroughs associated with Mendelism, the chromosomal theory of heredity, population genetics, the evolutionary synthesis, microbiology, and the emerging field of molecular biology. Until the 1960s, most French biology was more of a descriptive than an experimental field of science. When future Nobel laureate Jacques Monod focused on bacterial growth as the subject of his doctoral thesis at the Sorbonne, he was told by the head of the examining jury "This work is of no interest to the Sorbonne"—though Andre Lwoff, the director of a lab at Pasteur and a future Nobelist, had already arranged for Monod to have an appointment at the Institute Pasteur [19].

Whereas the French often viewed Americans as being quite provincial, most American graduate schools throughout much of the twentieth century expected their doctoral students to read one or two foreign languages. But in French universities until after the Second World War, most French biologists had to rely on French scientific journals because they could not read foreign languages. Moreover, the French system was relatively closed: it was a rare exception that someone could be a professor in a French university who did not have a French doctorate. This, combined with the highly centralized system, further stifled scientific creativity. Significantly, Andre Lwoff, Jacques Monod, and François Jacob did their Nobel Prize-wining work in a private research organization: Institut Pasteur. Moreover, Lwoff had quite diverse, cosmopolitan training. He had worked in the laboratory of Otto Meyerhof in Heidelberg and with David Keilin in Cambridge—two of the world's leading biochemists. And Monod and Jacob were well integrated into the American and British worlds of biology. Hence, their level of novelty as biologists at the Institute Pasteur during the 1950s was a notable exception to the style of work conducted there as well as elsewhere in France.

My data on these and a few other countries have demonstrated that during most of the twentieth century variations in the institutional environment in which biomedical research organizations and their laboratories were embedded had a strong impact on their capacity to be flexible in adapting to the rapidly changing global world of science, to produce highly creative scientists, and to make major discoveries.

The data also demonstrate that organizations or parts of organizations which had visionary leaders (scientists who internalized considerable scientific diversity) and which had intense communication among a staff with considerable scientific diversity tended to have more major discoveries and environments facilitating high levels of creativity than those ranking low on each of these characteristics.[3]

When research laboratories were embedded in organizational contexts having characteristics similar to those in table 2, multiple major discoveries occasionally occurred and they tended to have a number of scientists with high cognitive complexity. Examples included the Rockefeller Institute for Medical Research before 1945, the laboratory for Molecular Biology in Cambridge after 1962, a few of the Kaiser Wilhelm and Max Planck Institutes in Germany, and the Basel Institute for Immunology. The organizational contexts having multiple major breakthroughs tended to be highly flexible in their capacity to adapt to rapid changes in the world of science, to have high autonomy from their institutional environment, to have

3 The concept organizational context refers to those properties of the organization which most directly impinge on the discovery process within research laboratories.

research staffs reflecting a moderately high level of scientific diversity, to have leaders with a vision of the direction in which science was moving and the capacity to recruit scientific staff consistent with that direction, and to have an organizational culture which facilitated high communication among its staff through frequent and intense interaction with one another. Most organizations having these characteristics tended to be relatively small. When the laboratories were embedded in organizational contexts having low values on all the variables listed in table two, the organizations occasionally would have a major discovery—but rarely were there multiple major discoveries. Moreover, such organizations rarely had scientists who had high cognitive complexity [20].

When I studied the organizational context where biomedical research occurred in very large organizations, I found that their departments and/or labs were influenced by the structure and culture of the entire organization as well as the proximate characteristics of those subparts of the organization which directly impinged on research within laboratories. Large organizations tended to be quite differentiated between their core and subparts (being a small institute, program, or department) in a large, complex university. In large research organizations, there has tended to be considerable variation in the behavior and performance of the various subparts of the organization.

The more that large research organizations had the characteristics listed in table 3 (i.e., were very large, highly fragmented and differentiated into numerous subparts, each being further fragmented into sub-specialties), the more rare it was that any of its subparts had the characteristics listed in table 2. Organizations with hyperdiversity tended to be quite bureaucratic with a great deal of hierarchical authority, a configurative arrangement which tended to hamper the making of major discoveries. In such organizations, there tended to be relatively little communication among the many subunits. Thus organizations with the characteristics described in table 3 tended not to have had multiple discoveries. Even though an entire (usually large) organization tended to have the characteristics reported in table 3, it was always possible for some of the subparts (e.g., departments or institutes within a university) to have a few of the characteristics reported in table 2 [16].

Two large organizations—the University of Cambridge and Harvard University's College of Arts and Sciences—performed quite differently in the basic biomedical sciences from other large universities in the four countries of my study. Because each had a sizeable number of major breakthroughs, elsewhere I have conducted separate in-depth studies of each [14].

At Cambridge in the early part of the twentieth century, the university was very pluralistic and decentralized—i.e., lacking in strong hierarchical and bureaucratic structures. As a result of the strong reputation of the university, it was able to attract talented scientists and funding for research. Strong scientific leadership in physiology and biochemistry was able to create organizational contexts supportive of excellence and creative research in those two areas in the first half of the twentieth century. However, the university did not attract the same level of highly talented scientists and leadership in a number of other fields (e.g., zoology, anatomy). Thus these were not fields where major discoveries occurred [21].

Similarly at Harvard after World War II, the College of Arts and Sciences did not have strong hierarchical and bureaucratic structures, and it was able to attract talented scientists and leadership in the fields of biochemistry and molecular biology. In such an organizational context, multiple major discoveries occurred—but not in those departments which had low values on the concepts in table 2. On the other hand, large research organizations which were quite hierarchical and bureaucratic were unable to have sufficient flexibility and autonomy to have the potential for organizational contexts with multiple major discoveries in basic biomedical science (e.g., University of Michigan, University of Minnesota, University of Illinois, the Sorbonne).

Table 2

*Characteristics of organizational contexts facilitating the making of major discoveries**

Moderately high scientific diversity
Capacity to recruit scientists who internalize scientific diversity
Communication and social integration of scientists from different fields through frequent and intense interaction
Leaders who integrate scientific diversity, have the capacity to understand the direction in which scientific research is moving, provide rigorous criticism in a nurturing environment, have a strategic vision for integrating diverse areas, and have the ability to secure funding to achieve organizational goals
Flexibility and autonomy associated with loose coupling with the institutional environment

* These characteristics were derived from my intense, in-depth analysis of the organizational contexts in which major discoveries either occurred or did not occur through the twentieth century in Britain, France, Germany, and the United States.

Table 3

*Characteristics of organizational contexts constraining the making of major discoveries**

Differentiation:	*Organizations with sharp boundaries among subunits such as basic biomedical departments, the delegation of recruitment exclusively to department or other subunit level, the delegation of responsibility for extramural funding to the department or other subunit level.*
Hierarchical authority:	*Organizations were very hierarchical when they experienced centralized (a) decision making about research programs, (b) decision making about number of personnel, (c) control over work conditions, (d) budgetary control.*
Bureaucratic coordination:	*Organizations with high levels of standardization for rules and procedures.*
Hyperdiversity:	*This was the presence of diversity to such a deleterious degree that there could not be effective communication among actors in different fields of science or even in similar fields.*

* These characteristics were derived from intense, in-depth analysis of the organizational contexts in which major discoveries either occurred or did not occur through the twentieth century in Britain, France, Germany, and the United States.

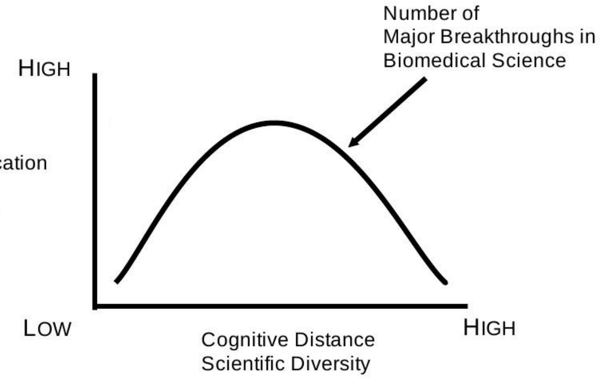
Figure 2 is a summary of one of the most important findings of the numerous case studies I have conducted. The figure refers to characteristics of organizational contexts: the horizontal axis is the degree of scientific diversity and the vertical axis is the degree of communication and social integration among scientists within an organization. Major discoveries tended to occur in organizational contexts in which there was moderately high scientific diversity and in which scientists who internalized moderate levels of scientific diversity were able to have relatively high degrees of communication and social integration with each other. As the degree of scientific diversity increased in organizational contexts, however, it became increasingly difficult for scientists with different backgrounds to have effective communication with each other. Good communication among diverse groups of scientists has tended to become especially difficult as the size of organizations and the number of sub-specialties expands.

In research organizations where there was very little scientific diversity, there were relatively few fundamental breakthroughs. At the left end of the horizontal axis of figure 2, we observe what happened when scientists worked in environments in which there was little scientific diversity. When scientists worked in environments with little scientific diversity—either because they were working alone or because the entire research organization and/or its labs had little scientific diversity—they tended to concentrate on a relatively narrow range of problems of interest primarily to highly specialized audiences. Highly specialized groups of scientists having the same mindset tended not to make major discoveries. My data demonstrate that the integration of scientific diversity was necessary if a laboratory was to have high levels of novelty.

Radically new ways of thinking emerged when individual scientists internalized a moderately high degree of scientific diversity and/or a group of scientists working together but from diverse backgrounds had intense and frequent interactions. These frequent and intense interactions among scientists with different backgrounds increased the likelihood that there could be fundamental new ways of thinking about a problem. When scientists from different backgrounds had intense and frequent interactions—sharing their own views to produce a new way of thinking about a problem—one or more of the individual scientists in the group had to internalize a great deal of scientific diversity or else communication was very difficult. The organizational context with multiple major breakthroughs tended to have a scientific leader who internalized a great deal of scientific diversity, just as a good chamber music group tends to have a leader who has knowledge about more than a single instrument.

The really successful scientific leaders not only had a vision of the direction in which science was moving and were able to move a group of scientists in that direction, but were also able to provide socio-emotive support among the scientific staff—a feature generally not noted in much of the literature about research organizations. Simon Flexner, the first Director of the Rockefeller Institute; Max Perutz, the first Director of the Laboratory of Molecular Biology in Cambridge; Salvador Luria in the Department of Biology at MIT during the

Figure 2:
The effect of communication and cognitive distance on making major breakthroughs in biomedical science.



1960s; and Bill Rutter in the Department of Biochemistry and Biophysics at the University of California San Francisco in the late 1960s had these rather rare qualities, as did Michael Foster in the Physiology Department and Frederick Gowland Hopkins in the Biochemistry Department of the University of Cambridge. My data demonstrate that individuals who had intense and frequent interactions with each other and who came from different disciplines, had to be capable of accepting severe criticism from one another without becoming angry and hurling insults at one another.

There were a variety of mechanisms whereby scientists were able to increase the degree of communication and social integration of scientific diversity: workshops and seminars; journal clubs for several laboratories; social events such as lunch and teatime at which scientists could carry on rich scientific discussions in an unplanned setting; weekend retreats; and special courses involving scientists from diverse backgrounds [20].

The quality of scientific leadership has influenced the extent to which scientific actors can be integrated into common endeavors, though the degree of integration is obviously constrained by the nature of the scientific problem which scientists are confronting and the organizational context within which the research is embedded. The structure and culture of the organizational contexts have placed constraints on the type of leaders who are recruited. While there is great variation in the quality of leaders in research organizations, certain kinds of leaders would rarely be recruited to head some kinds of organizations. For example, during the past quarter century, most large, bureaucratically oriented American research universities have tended to appoint presidents or chancellors who were essentially managers, facile and adroit politically in interacting with many different constituencies (faculty, students, legislators, donors, the media). They have tended to be skilled in raising money, managing large and complex budgets, and creating favorable public images for their organizations so that they can raise even more money. They have certainly not been scientific visionaries, and if they were, they would not have been recruited. The heads of these universities could just as well manage a government bureaucracy or large private company.

It has been in smaller research organizations, or occasionally in a subpart of a large organization, that one finds the type of scientific leader described in table two. One can hardly imagine that some of the recent Presidents of Rockefeller University—Nobel laureates Paul Nurse, Torsten Wiesel, David Baltimore, Joshua Lederberg—would have been recruited to be Chancellor of a huge university in the United States, or that the chancellor of one of these large universities would be recruited to head such small distinguished research organizations as the Rockefeller, the Scripps Research Institute in La Jolla, California, the Laboratory of Molecular Biology in Cambridge, or a Max Plank Institute in Germany.

There was organizational complementarity among the concepts in table two, meaning that each of these variables was complementary to the other. The higher the score an organization had on each variable, the easier it was to be high on the other, and the higher the values on each of the variables, the greater the likelihood that the organizational context would have major breakthroughs.

6. Changes in the Spatial Distribution of Scientific Creativity

With historical hindsight one can easily discern that over long periods of time there have been rises and declines of national systems of science in terms of the levels of scientific creativity. For example, from around 1735 to 1840 France was the world's center of scientific creativity. This was the era of Antoine Lavoisier, Pierre-Simon Laplace, and Claude Berthollet in physiology and chemistry, in addition to great advances in physics and mathematics. The French centralized state, combined with a robust economy, made for a renowned science system. But ultimately, it was the centralized system which led to the system's rigidity and ultimately the decline in the total quantity of creativity in the French system.

Next, the nexus of scientific creativity shifted to Germany, from the middle of the nineteenth century until the 1920s. The 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 Institutes, and the growth of science-based industries. In the first eleven years of 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 began to shift to Britain. Over the next half century, scientific funding from government and industry rose. A vigorous university system emerged, and the country boasted numerous Nobelists: physicists Joseph John Thomson, the father and son team of William and Lawrence Bragg, Ernest Rutherford, Paul Dirac, James Chadwick and John Cockcroft; biologists Archibald Hill, Frederick Hopkins, Charles Sherrington, Edgar Adrian, Henry Dale, Ernest Chain, Howard Florey, and Alexander Fleming; and chemists William Ramsay, Arthur Harden, Frederick Soddy, and Alexander Todd, among others. Then with the demise of the British Empire and the weakening of the British economy, the location of vast creativity in science shifted also. By the end of the Second World War, the United States had picked up the baton and still holds it.

The United States emerged from the Second World War as the world's economic superpower, facilitating its dominance as the world's center of scientific creativity. Since then American scientists have received more than half of the most prestigious awards in the biomedical sciences, such as Nobel, Lasker, Horwitz[4] and Crafoord Prizes. For many years United States researchers have dominated scientific journals, accounting for more than fifty percent of the top one percent of cited papers.

Each former scientific hegemon 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 centers of fiscal growth, 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 the emergence of creative centers elsewhere. The elite could not imagine that the centre would shift.

Meanwhile, fundamental changes in the American economy in the past few decades, the incremental changes in the mechanisms for funding governmental research grants, and the growth in the size of many universities with their expanding specialization and bureaucratization tend to be undermining the potential for the American system of science to socialize young scientists to engage in high-risk research and to be highly creative. If history is any guide, the decline of the American hegemony of scientific creativity has begun [16].

Increasingly over the last half century we have observed the emergence of large-scale, bureaucratic systems of science and increasing centralization in the funding of science—processes not conducive to the development and nurturing of creative scientists. Americans have led the way in the emergence of "big science," with, for example, the Manhattan Project, the Jet Propulsion Lab, Lawrence Livermore National Laboratory, Argonne and Brookhaven National Laboratories, or the Human Genome Project. Indeed in many fields there has been a shift to collective research. Even though creativity tends to be achieved by individuals, one of the virtues of large-scale science is the ability to organize sizable groups with different skills, ideas and resources. Teams produce many more papers than individuals, 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 one thousand citations [22].

In some fields, the transformation towards big science has built in irreversible constraints. During the past half century, the number of scientists in most American universities, research institutes and pharmaceutical companies has swelled. Many universities have become

4 Jewish Winners of the Louisa Gross Horwitz Prize," http://www.jinfo.org/Biology_Horwitz.html. (accessed 7 November 2011).

increasingly bureaucratic and fragmented, with huge departments and constructed like silos. As a result, many scientists have considerable difficulty in communicating across fields. 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 United States 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 size and inertia hampers these efforts as well as scientific creativity.

Scientists are increasingly evaluated by the number of papers they have authored, not by their level of creativity. Some seem to think that the number of scientific papers and creativity are one and the same, but two of the most creative biological scientists of the last century (Francis Crick and Fred Sanger) had their names on fewer than eighty papers in careers which extended more than forty-five years. At the same time, the increasing commercialization of science has tended to emphasize short-term scientific horizons and high publication rates. All these factors threaten the future of high creativity in science.

Excellence and creativity in science require nimble, autonomous organizations—qualities more likely to be found in small, highly autonomous research settings. Dozens of scientists who made major discoveries in my population of scientists did so in organizations with fewer than fifty full-time researchers. In recent decades, some of the most creative small research organizations in the biological sciences were Rockefeller University in New York, the Salk Institute in San Diego, the Basel Institute for Immunology, the Laboratory of Molecular Biology in Cambridge, UK, and three Max Planck Institutes in Germany. Many of the most important recent advances in the following subjects were made in relatively small research settings: the fundamental architecture of cells, how genetic information is encoded, and many of the molecular details of metabolism and signal transduction. In the past decade a number of 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).

My research suggests that scientific creativity could be enhanced if there were worldwide the development of one or two 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—the Howard Hughes Medical Institute's Janelia Farm in Virginia, the Santa Fe Institute in New Mexico, the Fred Hutchinson Cancer Center in Seattle, the Institute Para Limes in the Netherlands and the new Institute for Quantum Optics and Quantum Information in Austria. Obviously, this would not be an appropriate strategy in a number of scientific fields, but it would be desirable in those areas where small-scale science can function effectively.

The decline of the United States economy relative to those of the rest of the world is facilitating the distribution of scientific creativity across the globe. The increasing wealth of a number of societies is enabling them to lure back to their homelands many younger scientists trained abroad in the best centers of the world. All in all, it seems unlikely that we will witness for decades to come another unrivalled hegemonic center of scientific creativity in the mould of France, Germany, Britain and the United States. But wherever there are concentrations of highly creative scientists in the biological sciences, I would expect that they would be associated with the personal traits as described above and that the more creative scientists would be embedded in institutional and organizational environments similar to those described above [13].

Acknowledgements

I wish to acknowledge the generous and insightful assistance of Ellen Jane Hollingsworth and David Gear, both at the University of Wisconsin, who contributed to all aspects of this paper.

References

1 Hollingsworth, J. R. 2007, "High Cognitive Complexity and the Making of Major Scientific Discoveries," in Knowledge, Communication and Creativity, eds. A. Sales & M. Fournier (London and Thousand Oaks, California: Sage Publications), 129-155

2 Park, R. E. 1937, "Introduction," in The Marginal Man, E. V. Stonequist (New York: Charles Scribner's Sons), xiii-xviii

3 Simmel, G. 1908, "The Stranger," in The Sociology of Georg Simmel, ed. tr. K. H. Wolff (London: The Free Press of Glencoe Collier-Macmillan Ltd., 1964) 402-408

4 Root-Bernstein, R. S., 1989, Discovering (Cambridge, MA: Harvard University Press)

5 Root-Bernstein, R. S. & Root-Bernstein, M. M. 1999, Sparks of Genius (Boston, MA: Houghton Mifflin)

6 Suzuki, S. 1969, Nurtured by Love: A New Approach to Education (New York: Exposition Press)

7 Clark, R. 1971, Einstein: The Life and Times (New York: World Publishing)

8 Root-Bernstein, R. S. 2001, Leonardo, 34, 63–68.

9 Hoffmann, R. 1981, "Autobiography," in Les Prix Nobel (Stockholm, Sweden: Nobel Foundation), 168–72. Also available at http://ww.nobel.se/chemistry/laureates/1981/hoffmann-autobio.html.

10 Hoffmann, R. 1995, The Same and Not the Same (New York: Columbia University Press)

11 Polanyi, M. 1962, Personal Knowledge: Towards a Post-critical Philosophy (London, United Kingdom: Routledge)

12 Polanyi, M. 1966, The Tacit Dimension (London, United Kingdom: Routledge and Kegan Paul)

13 Hollingsworth, J. R., Karl H. M., & Hollingsworth, E. J. 2008, "The End of the Science Superpowers: Could the End of US World Dominance over Research Mark the Passing of National Science Giants", Nature, 454 , 412

14 Hollingsworth, E. J. 2013, Cambridge Scientists: Major Discoveries in Basic Biological Science, forthcoming

15 Deichmann, U. 1996, Biologists Under Hitler, tr. T. Dunlap (Cambridge, MA: Harvard University Press)

16 Hollingsworth, J. R., & Hollingsworth, E. J. 2011, "The Rise and Decline of Hegemonic Systems of Scientific Creativity", in Major Discoveries, Creativity, and the Dynamics of Science (Vienna: edition echoraum), 57-69

17 Sinding, C. 1999, Osiris, 14, 61

18 Boesiger, E. 1980, "Evolutionary Biology in France at the Time of the Evolutionary Synthesis," in The Evolutionary Synthesis, eds. E. Mayr and W.B. Provine (Cambridge, MA: Harvard University Press), 309-321

19 Jacob, F. 1995, The Statue Within: An Autobiography, tr. F. Philip (Cold Spring Harbor, N.Y.: Cold Spring Harbor Laboratory Press)

20 Hollingsworth, J. R. 2004, "Institutionalizing Excellence in Biomedical Research: The Case of Rockefeller University," in Creating a Tradition of Biomedical Research: The Rockefeller University Centennial History Conference, ed. D. H. Stapleton (New York: Rockefeller University Press)

21 Hollingsworth, J. R.,and Müller, K. H. 2008, "Transforming Socio-Economics with a New Epistemology", Socio-Economic Review, 6, 395

22 Wuchty, S., Jones, B. F., & Uzzi, B. 2008, Science, 316, 1036

Appendix I: Interviews for the Writing of this Paper[1]

*Seymour Benzer, Professor of Biology, California Institute of Technology. Interview in his office, 30 March 1994; at Cold Spring Harbor Laboratory, New York, 26 August 1995; at Neurosciences Institute, San Diego, California, 17 March 1996; in his office, 22 December 1999.

*Paul Berg, Professor of Biochemistry, Stanford University School of Medicine. Interview in his office, 6 May 2003.

*James Black, Professor, King's College London. Interview at McGill University, 23 September 2004.

*Günter Blobel, Professor at Rockefeller University and HHMI investigator. Interview in his office, 12 April 1995; in his office, 16 March 2001, 18 March 2001, 21 December 2004, 13 October 2006, 12, 14 March 2007, 4 December 2008.

*Baruch S. Blumberg, Professor, Fox Chase Cancer Center (Philadelphia). Interview at Rockefeller Foundation Study Center, Bellagio, Italy, 21 May 1984; at Institute for Advanced Study, Princeton, NJ, 30 November, 2 December 2008.

*Sydney Brenner, Professor Salk Institute, and Former Director of Laboratory of Molecular Biology (Cambridge, UK). Interview in La Jolla, California, 7 April 2003; in Almen, The Netherlands, 8 October 2007.

Alec Broers (Sir). Professor and Vice-Chancellor, University of Cambridge. Interview in his office 23 April 2002.

William J. Butterfield (Baron Butterfield), former Vice-Chancellor University of Cambridge. Interview in his home, 12 July 2000.

Henry Chadwick (Sir), Former Master Peterhouse College, University of Cambridge. Former Regius Professor, University of Oxford; former Regius Professor, University of Cambridge. Multiple interviews at Rockefeller Foundation Study Center, Bellagio, Italy, June 1994; at his home in Oxford, 13 April 1997; at this author's home (Madison, Wisconsin) 15 April 1998.

*Francis Crick, President Emeritus and Distinguished Professor, Salk Institute; former scientist at Cambridge University and at the Laboratory of Molecular Biology. Interview in his office in San Diego, 6 March 1996, 11 March 1998; at UCSD 6 June 2002.

*James E. Darnell, Jr., Professor, Rockefeller University. Interview in his office, 10 April 1995. Other interviews in his office, 8 March 2001, 18 April 2001, 29 May 2001, 4 December 2008.

1 * Indicates a recipient of Nobel, Lasker, Crafoord or Louisa Gross Horwitz Prizes

Ute Deichmann, Geneticist and Historian of Science, Institute of Genetics, University of Köln and Ben Gurion University, Israel. Interview in Köln, 17 April 2004.

Carl Djerassi, Professor of Chemistry, Stanford University. Interview in Madison, Wisconsin, 18 May 1995; 7 October 1997 in Department of Chemistry, University of Wisconsin (Madison).

Paul Doty, Mallinckrodt Professor Emeritus of Biochemistry, Harvard University. Interview in his office, 3 May 1995; at his home in Cambridge, Massachusetts, 19 December 2002.

*Renato Dulbecco, Emeritus President and Distinguished Professor, Salk Institute; Former Professor California Institute of Technology. Interview in his office in San Diego, 23 February 1996. Second interview in his office, 22 May 2000.

*Gerald Edelman, Research Director, The Neurosciences Institute, San Diego, California and former Professor and Dean, Rockefeller University. Interviews in Klosters, Switzerland, 17 January 1995; at Neurosciences Institute (NSI), 13 January, 16 January, 19 January, 30 January, 14 February, 20 February, 22 February, 5 March, 16 March, 17 March 1996, 12 February 1998, 4 April, 11 April, 18 November 2000, 1 May, 26 May 2006; telephone interviews, 3 April 2001, 18 August 2008.

*Robert G. Edwards, Professor Emeritus of Physiology, Cambridge University. Interview at Churchill College, Cambridge, 21 February 2006.

*Manfred Eigen, Professor, Max-Planck Institut für Biophysikalishe Chemie, Göttingen, Germany. Interview in Klosters, Switzerland, 16 January 1995.*Gertrude Elion, Scientist Emeritus, The Wellcome Research Laboratories, Research Triangle Park. Interview in her office. 17 March 1995.

*Daniel Carleton Gajdusek, Chief of the Laboratory for Slow Latent and Temperate Virus Infections and Chief of the Laboratory for Control Nervous System Studies at the National Institute for Neurological Disorders and Stroke. Interview at Neurosciences Institute, San Diego, California, 11 March 1996.

*Walter Gilbert, Carl M. Loeb University Professor at Harvard University. Interview in Chicago, 14 October 1993, in his office at Harvard University 26 April 1995.

*Joseph Goldstein, Professor, Department of Molecular Genetics, University of Texas Southwestern Medical Center. Interview at Rockefeller University, 13 March 2007.

*Paul Greengard, Professor at Rockefeller University. Interview in his office, 16 May 2001.

Stephen C. Harrison, Higgins Professor of Biochemistry and Molecular Biology and HHMI Investigator, Harvard University. Interview in his office, 18 December 2002.

*Tim Hunt, Head of the Cell Cycle Control Laboratory at Cancer Research UK. Interview at his home north of London, 13 May 2006.

*Andrew Huxley (Sir). Emeritus Professor of Physiology, University College, London, Former Master of Trinity College, University of Cambridge, and former President of the Royal Society. Interviews at Trinity College, 11 July 2000, 20 January, 4 March 2002, 1 February 2006.

*Francois Jacob, Senior Scientist, Institut Pasteur. Interview at Cold Spring Harbor Laboratory, New York, 24 August 1995.

*Eric R. Kandel, Director of Center for Neurophysiology and HHMI Investigator, Columbia University School of Physicians and Surgeons, member of Board of Trustees, Rockefeller University. Interview at Columbia University, 19 April 2001.

*Aaron Klug, former Director, Laboratory of Molecular Biology (LMB), Cambridge UK, President of the Royal Society, Honorary Fellow of Trinity College. Telephone interview, 24 May 1999; in his office at LMB, 11 July 2000; at Trinity College, Cambridge, 3 April 2002.

*Arthur Kornberg, Emeritus Professor of Biochemistry, Stanford University School of Medicine (Nobel laureate in Physiology or Medicine, 1959). Interview in his office, 5 May 2003.

*Joshua Lederberg, President Emeritus, Rockefeller University. Former Chair, Medical Genetics, Stanford University School of Medicine and former Professor of Genetics, University of Wisconsin (Madison). Interviews at Rockefeller University, 16 September 1993, 13 April 1995; telephone interview, 27 August 1999; interviews in his office 25 January 2001, 4 April 2001.

*Rita Levi-Montalcini, Professor Emeritus of Biology, Washington University (St. Louis). Interview at her home in Rome, Italy, 15 June 1995.

*Arnold Levine, President Rockefeller University. Interview in his office, 14 May 2001.

Richard C. Lewontin. Alexander Agassiz Research Professor, Harvard University. Interview in his office 18 December 2002; at National Institutes of Health, Bethesda, Maryland 5 December 2005.

*Roderick MacKinnon, Professor Rockefeller University and HHMI Investigator. Interview in his office, 1 March 2001.

Hubert Markl, President, Max-Planck-Gesellschaft zur Förderung der Wissenschaften, Munich, Germany, Interview in Bonn, Germany, 9 July 1996; in his office in Munich, 15 June 1998; at Schloss Ringberg in Bavaria, 19 April 2002.

*Bruce Merrifield, John D. Rockefeller, Jr. Emeritus Professor, Rockefeller University. Interview in his office 11 February 2000.

*Matthew Meselson, Thomas Dudley Cabot Professor of the Natural Sciences, Department of Molecular and Cellular Biology, Harvard University. Interview in Los Angeles, 8 February 2003.

*Daniel Nathans, Professor, Department of Molecular Biology and Genetics, Johns Hopkins University, Baltimore. Interview in his office 21 July 1997.

*Paul Nurse, President, Rockefeller University. Interviews in his office, 23 December 2004, 15 October 2006, 13 March 2007, 5 December 2008.

*Max Perutz, former Director, Laboratory of Molecular Biology, Cambridge, UK. Interview at Peterhouse College, Cambridge, 15 March 1997; at Laboratory of Molecular Biology, 11 June 1999.

*John Polanyi, Professor, University of Toronto. Interview at the Center for Advanced Cultural Studies, Essen, Germany, 5 September 2001.

*Mark Ptashne, Professor, Memorial Sloan-Kettering Cancer Center and former Professor and Chair, Department of Biochemistry and Molecular Biology, Harvard University. Interview in his New York City residence, 24 May 2001.

*Lord Rees of Ludlow (Martin Rees), President of the Royal Society of London, Master of Trinity College, Cambridge, Astronomer Royal and Royal Society Research Professor at Cambridge University. Interview at Master's Lodge, Trinity College, 14 April 2006. Professor of Institute of Astronomy, Fellow of King's College, Cambridge, Member Board of Trustees Institute for Advanced Study, Princeton; at Trinity College, 30 March 2002.

*Robert Roeder, Professor at Rockefeller University. Interviews at Rockefeller University 24 April 2001, 8 May 2001.

Harry Rubin, Professor of Molecular and Cell Biology, University of California, Berkeley. Interview in his office, 4 January 1995.

*Fred Sanger, Emeritus Staff, Laboratory for Molecular Biology, Cambridge, United Kingdom. Interview at Emmanuel College, University of Cambridge, 7 June 1999.

*Oliver Smithies, Professor of Molecular Genetics and Pathology, University of North Carolina (Chapel Hill). Former President of Genetics Society of America. Interview in his office in Chapel Hill, 30 March 1996.

*Solomon Snyder, Professor and Director of Neuroscience, Johns Hopkins University. Interview in his office 18 July 1997.

Charles Stevens, Professor, Salk Institute. Interview in his office, 13 December 2000.

*Howard Temin, Professor in McArdle Cancer Laboratory, University of Wisconsin (Madison). Interview at McArdle Cancer Laboratory, 26 November 1993.

*Harold Varmus, Director of the National Institutes of Health and former Professor at University of California, San Francisco. Interview in his office, Bethesda, Maryland, 6 March 1995.

*Bert Vogelstein, Professor of Oncology and HHMI investigator, Johns Hopkins University. Interview in his office 18 July 1997.

*James D. Watson, Director, Cold Spring Harbor Laboratory, New York. Interview at Cold Spring Harbor, 24 August 1995, and at Neurosciences Institute, San Diego, 20 February 1996.

*Don C. Wiley, John L. Loeb Professor of Biochemistry and Biophysics, Harvard University. Telephone interview, 4 November 1999.

David Williams (Sir), former Vice Chancellor, University of Cambridge. Interview at Emmanuel College, University of Cambridge. 8 June 1999.

*Edward O. Wilson, Pellegrino University Professor and Curator of Entomology, Museum of Comparative Zoology, Harvard University. Interviews in his office, 4 May 1995, 17 December 2002.

Ernst-Ludwig Winnacker, President Deutsche Forschungsgemainschaft. Interview in Max Planck Institute for Study of Societies, Köln, Germany, 1997; at Schloss Ringberg in Bavaria, 19 April 2002.

Appendix II: Concepts and data

II.1 Indicators of Major Discoveries[1]

1. Discoveries recognized by the Copley Medal, awarded since 1901 by the Royal Society of London, insofar as the award was for basic biomedical research.
2. Discoveries recognized by a Nobel Prize in Physiology or Medicine since the first award in 1901.
3. Discoveries recognized by a Nobel Prize in Chemistry since the first award in 1901, insofar as the research had high relevance to biomedical science.
4. Discoveries recognized by ten nominations for a Nobel Prize in Physiology or Medicine in any three years prior to 1940.2
5. Discoveries recognized by ten nominations for a Nobel Prize in Chemistry in any three years prior to 1940 if the research had high relevance to biomedical science.5
6. Discoveries identified as prizeworthy for the Nobel Prize in Physiology or Medicine by the Karolinska Institute committee to study major discoveries and to propose Nobel Prize winners.5
7. Discoveries identified as prizeworthy for the Nobel Prize in Chemistry by the Royal Swedish Academy of Sciences committee to study major discoveries and to propose Nobel Prize winners.4 These prizeworthy discoveries were included if the research had high relevance to biomedical science.
8. Discoveries recognized by the Albert Lasker Basic Medical Research Award.
9. Discoveries recognized by the Louisa Gross Horwitz Prize for Biology or Biochemistry Research.
10. Discoveries recognized by the Crafoord Prize in Biosciences, awarded by the Royal Swedish Academy of Sciences.

II.2: Data

Altogether there were three hundred twenty-four major discoveries. My goal has been to understand the personal traits and organizational characteristics both associated with and not associated with the making of major discoveries. I have focused not only on the scientists associated with these discoveries but also on samples of large numbers of scientists who never made major discoveries but were members of the United States National Academy of Sciences, the Royal Society of London, and other major academies. My efforts were

1 Because I did not want this project to focus exclusively on those scientists receiving Nobel Prizes, the analysis has included other indicators of major discoveries as well.

2 I have had access to the Nobel Archives for the Physiology or Medicine Prize at the Karolinska Institute and to the Archives at the Royal Swedish Academy of Sciences in Stockholm for the period from 1901 to 1940. I am most grateful to Ragnar Björk, who did most of the research in the Karolinska Institute's archives to identify major discoveries according to the indicators in this table. Because the archives are closed for the past fifty years for reasons of confidentiality, I have used other prizes (Lasker, Horwitz, Crafoord) to identify major discoveries in the last several decades.

designed to determine if there were substantial differences in both groups in their individual traits as well as societal, organizational, and laboratory environments. My colleagues and I conducted in-depth interviews with more than five hundred of the leading basic biological scientists in these four countries, worked in numerous archives in the four countries, read hundreds of biographies and other kinds of monographs, and investigated in varying degrees of depth approximately seven hundred fifty research organizations.

I am extremely indebted to Ellen Jane Hollingsworth, David Gear, Jerald Hage, and Ragnar Björk for assistance in carrying out this research.