The Dynamics of American Science: An Institutional and Organizational Perspective on Major Discoveries[1]

J. Rogers Hollingsworth

This paper is a part of a research program analyzing how institutional and organizational factors facilitate or hamper the making of major discoveries in basic biomedical science.[2] Most of the paper focuses on research organizations and institutions in the United States, though there are occasional soft comparisons with the institutional environments and organizations of other societies. The research program as a whole examines research organizations in Britain, France, Germany, and the United States throughout the twentieth century.

Critical to this paper is the definition of a major discovery. A major breakthrough or discovery 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 breakthrough in biomedical science was a radical or new idea, the development of a new methodology, or a new instrument or invention.[3] 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 or local knowledge, if not both.[4]

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1 I am very grateful to Wolfgang Streeck, from whom I learned much about the way institutional environments influence the performance of organizations. Over many years, Jerald Hage has been my co-investigator in the study of radical scientific innovations. Likewise, my colleague David Gear has been of inestimable assistance in all my research. But my greatest debt is to Ellen Jane Hollingsworth, who, over the years, has been my collaborator in studying how institutions and organizations either facilitate or hamper the making of major scientific discoveries over time and across organizations.

2 For this paper, I draw on the study done in collaboration with Ellen Jane Hollingsworth and Jerald Hage of 291 major discoveries.

3 This way of thinking is very different from the rare paradigm shifts analyzed by Thomas Kuhn in *The Structure of Scientific Revolutions* (1962). Major breakthroughs in basic biomedical science, as defined here, occur within the paradigms about which Kuhn wrote.

4 Depending on the scientific community to operationalize this definition, I consider major discoveries to be research that received one of the following forms of recognition: (1) the Copley Medal, awarded since 1901 by the Royal Society of London, insofar as the award was for basic biomedical research, (2) the Nobel Prize in Physiology or Medicine since the first award in 1901, (3) the Nobel Prize in Chemistry since the first award in 1901, insofar as the research

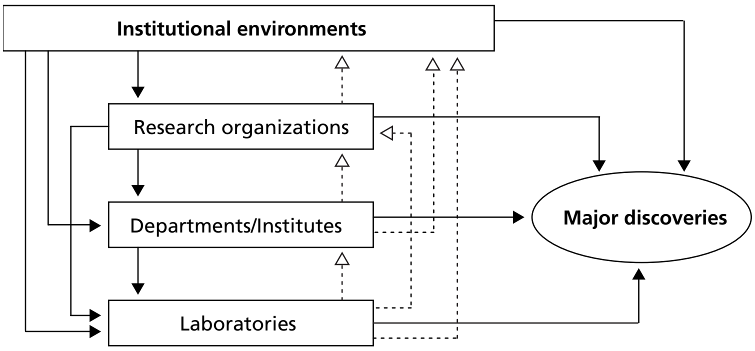
The analysis is multilevel in nature. Research usually takes place in laboratories in departments or divisions that are part of an organization; in turn, such research organizations are embedded in a larger institutional environment. Figure 1 is a simplified perspective of the way each of these levels influences the process of making major discoveries. One of the major challenges facing the scientific community is to understand how activities at one level of analysis are related to those at other levels (Hollingsworth/Boyer 1997). As the social science community lacks a good understanding of the way processes at multilevels of societies operate, this paper makes a modest contribution toward explaining how interactions at multiple levels influence major scientific discoveries. The paper's perspective is nonlinear and co-evolutionary. The heavy downward arrows in Figure 1 indicate the dominant type of influence which institutions and organizations exert on laboratories and researchers. The direction is not one way, for activities at the level of the laboratory influence the behavior of entire organizations as well as institutional environments. Collectively, all of these factors help to explain why there is variation across laboratories in organizations, across organizations in a society, and across societies themselves when it comes to making major discoveries. While each of these four levels identified in Figure 1 is constantly changing, the institutional environment is the most enduring

had great relevance to biomedical science, (4) ten nominations in any three years prior to 1940 for a Nobel Prize in Physiology or Medicine, (5) ten nominations in any three years prior to 1940 for a Nobel Prize in Chemistry if the research had great relevance to biomedical science, (6) considered prizeworthy for the Nobel Prize in Physiology or Medicine by the Karolinska Institute committee, which prepared a short list of possible prizewinners and recommended the winner(s), (7) considered prizeworthy for the Nobel Prize in Chemistry by the Royal Swedish Academy of Sciences committee, which prepared a short list of possible prizewinners and recommended the winner(s) (if the research had great relevance to biomedical science), (8) the Arthur and Mary Lasker Prize for basic biomedical science, (9) the Louisa Gross Horwitz Prize in basic biomedical science, (10) the Crafoord Prize, awarded by the Royal Swedish Academy of Sciences, for biomedical science. 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. The archives are closed for the past 50 years for reasons of confidentiality, and I have used other prizes (Lasker, Horwitz, Crafoord) to identify major discoveries during the latter part of the twentieth century. My concern is not whether proper credit was assigned to individual scientists for major breakthroughs. Rather, I seek to understand the structure and culture of the organizational context where research did or did not result in a major discovery. I have studied organizations, departments/institutes, and laboratories, as well as the interactions among individuals.

The research summarized here is based on a great deal of archival research, many interviews, and wide reading in many scientific fields. Archives have been used in the United States (e.g., Rockefeller Archive Center, American Philosophical Society, University of Wisconsin, Caltech, University of California Berkeley, University of California San Francisco, University of California San Diego, Harvard Medical School) and in Great Britain and Europe. I have conducted more than 450 in-depth interviews with scientists on both sides of the Atlantic.

and resistant to change. Actors at lower levels are greatly constrained by the norms, rules, and systems of rules that, by definition, constitute the institutional makeup of a society.

Figure 1 Factors at Multiple Levels Influencing Major Discoveries



1 Institutional Environments and Research Organizations

The institutional environments of research organizations consist of a variety of variables, all of which are treated equally here. Institutional environments range from weak to strong. Weak institutional environments exert only modest influence (1) over 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 existence of norms that socialize young people to undertake high-risk research).

Strong institutional environments are at the opposite end of the continuum on each characteristic. France is an example of a country that tended to have a strong institutional environment throughout the twentieth century, while research organizations in the United States have been embedded in a relatively weak institutional environment. However, institutional environments of societies change over time, and such changes influence the capacity of a society to make major scientific discoveries. The data on the institutional environments of these four countries suggest that 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, etc. This perspective resonates with the concept of institutional complementarity, found in a variety of work within social science literature.[5]

The institutional environment in which research organizations are embedded has an impact on organizational behavior. The stronger the institutional environment is, the greater the organizational isomorphism – a factor that results in less diversity among the types and behavior of research organizations. When organizational isomorphism is high, organizations tend to converge in their behavior and culture. On the contrary, in weak institutional environments, diversity is greater with regard to types of research organizations and the structure and culture of the organizations. I have found that such a society possesses greater potential for multiple scientific breakthroughs (Hollingsworth 2004; Hollingsworth/Hollingsworth/Hage 2006). In societies in which external controls over organizations are highly institutionalized and strong, connectedness[6] between research organizations and their institutional or external environments has generally been so strong that research organizations have had relatively little autonomy with which to pursue independent strategies and goals. Conversely, the weaker the institutional environment in which research organizations have been embedded, the greater the organizational autonomy and flexibility to develop new knowledge and to be highly innovative. Hence, in societies where institutional environments have been the most developed, rigid, and strong, fewer radical innovations have occurred in basic and applied science.

Heterogeneity in the types of research organizations has tended to be greater in weak institutional environments than in strong ones. In the United States, there have long been many more types of universities than in Germany, where universities embedded in a strong institutional environment resemble one another much more (Ben-David 1977). In the United States, we find small, elite, private universities (Rockefeller University, California Institute of Technology, Rice University), medium-sized private universities (Johns Hopkins University, University of Chicago, Vanderbilt University, Princeton); and large private universities (Harvard, Stanford, MIT, NYU). In addition, there are the large public universities in California (Berkeley, UCLA, UCSB, UCSD) and the Midwest (Michigan, Indiana, Wisconsin, Illinois, Minnesota). Historically, each type of university featured a distinct type of population, somewhat different from other types of research organizations, in part because their dominant competencies were not easily learned or transmitted (McKelvey 1982: 192).

5 On the concept institutional complementarity, see Crouch et al. (2005).

6 On the concept of organizational and institutional connectedness, see Hage/Hollingsworth (2000).

Table 1 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 among 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

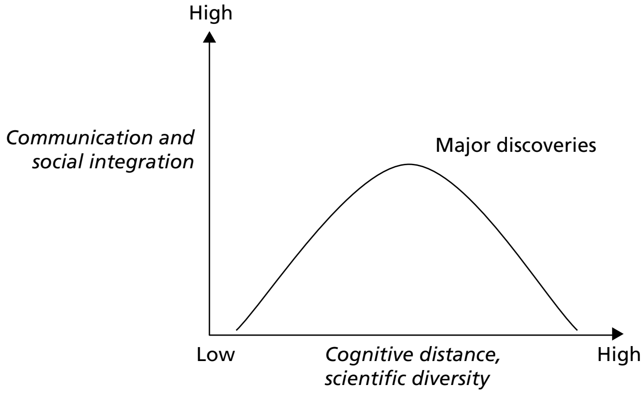
Of course, in both strong and weak institutional environments every organization is unique, meaning that heterogeneity always exists among organizations. Even if weak institutional environments lead to more heterogeneity among types of organizations, forces are nevertheless at work that increasingly lead to organizational isomorphism both across and within organizational types.

The society likely to have numerous breakthroughs is one with a weak institutional environment that permits a high degree of nonconformity and high-risk research. My in-depth, cross-national, and cross-temporal organizational study of 291 major discoveries in the twentieth century demonstrates that major discoveries have tended to occur more frequently in organizational contexts that were relatively small and had high degrees of autonomy, flexibility, and the capacity to adapt rapidly to the fast pace of change in the global environment of science. As Table 1 demonstrates, such organizations tended to have moderately high levels of scientific diversity and internal structures that facilitated the communication and integration of ideas across diverse scientific fields.[7] These organizations tended to have scientific leaders with a keen scientific vision of the direction in which new fields in science were heading and the capacity to develop a strategy for recruiting scientists capable of moving a research agenda in that direction.

Organizational contexts featuring such characteristics were Rockefeller University, the California Institute of Technology, the Salk Institute, and the Johns Hopkins University Medical School. Scientists at the relatively small Rockefeller University made more major discoveries in basic biomedical science than any

7 The results reported in Tables 1 and 2 were derived from an analysis of major research universities across the twentieth century. In the United States, there were only about 15 such universities in 1920, and approximately 60 by 2000. These were doctoral-research intensive universities. With few exceptions, these universities awarded 40 or more doctoral degrees per year across at least 10 academic disciplines.

Figure 2 The Impact of Communication and Cognitive Distance on Major Discoveries



other organization in the world during the twentieth century (Hollingsworth 2004; Hollingsworth/Hollingsworth 2000).

Figure 2 portrays the kind of organizational context in which major discoveries are more likely to occur. These contexts possess a moderately high degree of scientific diversity and a high level of communication among scientists in diverse fields of science. Of course, as organizations acquire more and more diverse fields of science, they run up against limits to their ability to maintain communication across diverse fields.

Even in societies with relatively weak institutional environments, most organizational contexts hamper the making of major discoveries. Over time, most research organizations tend to become relatively large and more bureaucratic. They are divided into an increasing number of scientific disciplines, and communication diminishes among scientists working in the various fields within the organization (see Table 2). Unlike Rockefeller University, most research universities are structured around departments and academic disciplines: for that reason they lack organizational flexibility and acquire a great deal of organizational inertia – since academic departments have a tendency to continue working in the same general problem areas.

Table 2 Characteristics of Organizational Contexts Constraining the Making of Major Discoveries

Differentiation	Organizations with sharp boundaries among subunits, 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.

2 Institutional Environments and Isomorphism within and across Research Organizations

Societies vary in their capacity to produce major discoveries over time because they are influenced in various ways by several historical processes, notably organizational isomorphism and path dependency. Path dependency reminds us that the way things were previously organized influences the way they are organized today. Still, institutional environments, organizations, and individual actors are always changing. The stronger the institutional environment is, the greater the degree of organizational isomorphism and the greater the similarity in path-dependent processes among organizations. Even in societies with weak institutional environments, there are forces which lead over time to greater degrees of homogeneous behavior (i.e., organizational isomorphism) across and within organizations. Different populations of organizations in the same society develop a set of competencies and routines that become institutionalized but remain societally specific. As a result of these competencies, actors in both different and similar organizations engage in a great deal of common learning and socialization. Scientists, technicians, and administrators from different types of organizations in the same society acquire a great deal of common organizational know-how that is transmitted across time and organizations. Some years ago, DiMaggio and Powell (1983) picked up on these ideas when they pointed out that organizations in the same society engage in many "mimetic processes." Others (Hodgson 2003) developed the argument that routines are organizational metahabits, which diffuse across populations of organizations in a particular institutional environment. To understand homogenizing forces across and within organizations in the same institutional environment, analysts have increasingly focused on control mechanisms of individuals in their socialization processes – although the control replicators are called many different things in the literature: memes, culturgens, routines, and comps. Whatever the term, social scientists have been focusing for some time now on the way competition among organizational actors in an institutional environment is suppressed by norms, rules, habits, and conventions at the group and organizational levels. Isomorphic pressures are especially strong when actors in highly saturated environments are competing for the same finite resources (McKelvey 1982).

Isomorphism, no matter how powerful a force, certainly does not sweep through history unimpeded. It occurs at a very moderate rate, constrained by many forces. One factor retarding organizational isomorphism is the existence of diverse types of research organizations in a society. Many years ago, Stinchcombe (1965) made the astute observation that organizations founded at different points in time, even those of the same type, are influenced in their behavior for long periods by the cultural attributes of the social technologies current at the time of their foundation. When Stinchcombe made his observation, social scientists had not explicitly developed the concepts of path dependency and organizational isomorphism, but his emphasis is clearly suggestive of a path-dependency perspective. Stinchcombe was making the profound point that organizations do not necessarily closely track changes in their environment, but are somewhat inert, preserving certain nonadaptive qualities that often have deleterious effects on their capacity to be highly adaptive to their environments. Thus they resist isomorphic pressures; as a result, population heterogeneity persists.

There is a substantial body of literature suggesting that continuously high levels of radical innovation in modern societies require diversity in organizational forms and ideas, heterogeneity in organizational structures, and institutional environments with ample resources to nurture radical innovations (Hage/Hollingsworth 2000). Individual societies continuously confront contradictory pressures. On the one hand, they are subjected to processes that move organizational populations toward greater homogeneity and uniformity. On the other, homoeostatic forces within populations of specific types of organizations constrain evolutionary change and preserve nonadaptive forms, facilitating organizational inertia (Mayr 2001). If a society is to be continuously creative and make radical innovations, it must have sustained variation and diversity in organizational forms and ideas, which are more likely to flourish in weak institutional environments.

However great the forces of isomorphism among populations of organizations are, new organizational forms may continue to emerge from time to time. Unfortunately, we lack sufficient theoretical tools to specify when and where radically new organizational types will emerge. For theoretical insights into this problem, some of our best sources are the biological literature on the processes of speciation. It is useful to think of the emergence of new organizational forms as organizational mutants. Mutations occur all the time, among both biological and organizational species. However, most do not "take hold" as they are outnumbered in their population environments, crowded out, and "rapidly dissipate through the normal intermixing process" (Astley 1985: 232). Moreover, we know from numerous population-ecology studies that new organizations have low survival rates.

Thought of as a mutation, a new organizational form is more likely to survive if it occurs in organizational environments that are sparsely populated and have ample resources to support such new development, and if it is not crowded out by the normal process of intermingling with other types of organizations. New surviving forms tend initially to be relatively autonomous from their environments. In such environments, organizational speciation may occur, and in the short term, a new form may be immune to the pressures of organizational isomorphism. Environments with resources exceeding demand offer a greater opportunity for a new organizational form to survive than do more competitively saturated environments (McKelvey 1982).

One example of the emergence of a new form of research organization is the establishment of several research institutions in the United States after 1960: the Salk Institute, the Scripps Research Institute (both in La Jolla, California), and the Fred Hutchinson Cancer Research Center (Seattle, Washington). What was novel about these institutions compared with older ones (the Scripps Institute of Oceanography, the Rockefeller Institute, the various Carnegie Institutes, the Laboratory of Molecular Biology in the UK, the Institut Pasteur, the various Max Planck Institutes) was that this new form of research institute had no endowment, no permanent patron, and no assured source of support. These institutes, emerging in newly developing research environments in Southern California and Seattle, were managed by entrepreneurs skilled at raising money in the distinctive regional entrepreneurial landscape of the West Coast, where thousands of adventurous investors and philanthropists were in search of new, local investment niches. Traditional sources of capital – banks, the federal government, and more conservative philanthropists in the East – tended to view these ventures with skepticism. Significantly, Silicon Valley emerged on the outskirts of Palo Alto, California, and the biotechnology industry also had much of its early success in the sparsely populated California landscape, not in the older centers of the United States where the industrial organizational density was quite high.

Since clusters of major discoveries tend to occur within relatively small organizations (see Table 1 and Figure 2), why is it that they may also occur within a large organization that is separated internally into various departments? Such rare occurrences tend to take place when the following conditions exist:

- The organization must be extremely decentralized (permitting the scientists making major discoveries to enjoy a high degree of autonomy and flexibility).
- The actors within the organization must have access to sufficiently diverse types of resources so that their scientific practices and administrative routines are not crowded out by those already institutionalized in the host organization.

The subunits of organizations where these clusters occur tend to have most of the characteristics listed in Table 1. According to evolutionary logic, those making major discoveries in a new scientific area of research tend to be in a better position to escape the institutionalized, homogenizing pressures of the organizations and to possess the autonomy to intermix, interbreed, and reproduce their own intellectual progeny within their particular subunit of the larger organization.

The occurrence of a cluster of major discoveries in an organization, especially in a single department over 30 or 40 years, is extraordinarily rare. Such a cluster of discoveries occurred in the Faculty of Arts and Sciences of Harvard University between the mid-1950s and the mid-1970s following the establishment of two new departments: the Department of Biochemistry and Molecular Biology, and the Department of Organismic and Evolutionary Biology. From each of these departments came a number of major discoveries. Significantly, these new departments were not encumbered by the inertia of the past.[8]

Over time, however, departments establish institutionalized routines, as do universities, and inertial processes set in, making it difficult for a highly creative subunit to continue being so innovative. At Harvard, as elsewhere, the level of innovativeness in a highly creative department eventually declined. Even organizations once highly decentralized, in which each subunit enjoyed a high degree of autonomy, tend to institutionalize a set of routines across the organization, thereby establishing interlocking and conditional behaviors for all subunits of the organization.

8 The brief generalizations about these two Harvard departments are based on numerous interviews with scientists and administrators, as well as on archival materials at Harvard. These materials are reported in much more detail in the forthcoming study, Hollingsworth/Hollingsworth/Hage (2006).

Initially these two Harvard departments were headed by outstanding leadership with visionary agendas and staffed by scientists researching areas that were moderately high in diversity and very highly integrated scientifically (see Table 1). Even though each scientist within the department tended to pursue a separate body of research, the work was highly complementary to the research program of the entire department, which possessed a distinctive culture that glued it together.

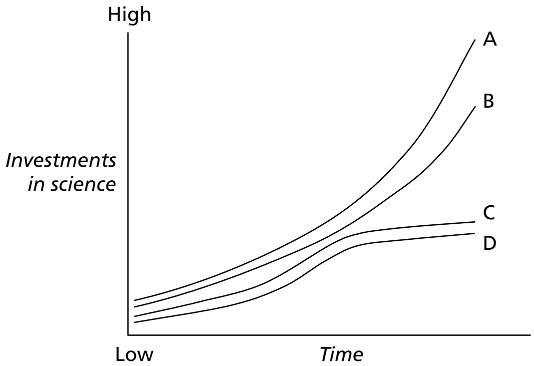
Eventually the distinctive scientific excellence of these departments declined. The scientific agenda of the new departments diffused to other organizations throughout the world, and many of the original members of the departments retired, died, or left. As scientific practices became routinized, no other leader emerged with a radically new agenda, capable of transforming the departments again into those on the cutting edge of science. The routines of the larger organization in which the departments were embedded slowly penetrated the departments. For all of these reasons, it is difficult for a research department to remain on the cutting edge of research for more than two or three decades. It is possible for a new department with a new scientific agenda to emerge, but seldom does such a department then proceed to produce clusters of pioneering discoveries in science. Rare indeed are the equivalents of within-organization mutations that are able to "take hold." Over the longer term, the distinctiveness of a "new departmental species" diminishes as it is constrained by the routines of the rest of the organization and other organizations in its institutional environment.

3 The Shift from a Weak to a Stronger Institutional Environment

Over time, the dynamics of the scientific enterprise embedded in a weak environment cause the institutional environment to become a much stronger one, and the institutional environment is transformed. In turn, the stronger institutional environment alters the dynamics of the society's system of science.

What is it about the scientific enterprise that leads to change in the institutional environment of research organizations? For some time, the world has been experiencing an enormous expansion of information and knowledge, which in turn begets ever more information and knowledge. For well over a century, the number of scientific papers and journals has been increasing exponentially, fueled by increases in the number of scientists and financial resources for science. For many years, developed economies also witnessed an exponential increase in the number of scientists and in the percentages of gross domestic

Figure 3 Historical Growth of Investments in Science



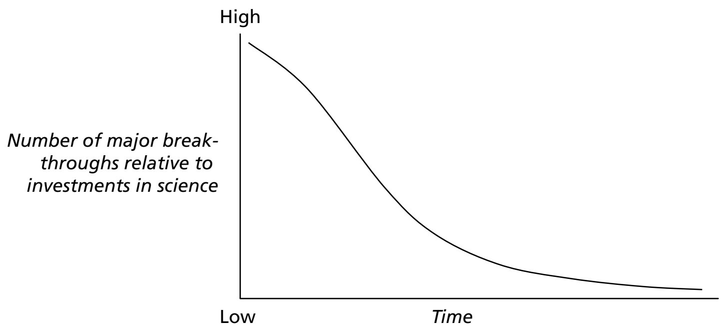
A Number of scientific papers
B Number of scientific journals
C Percent of workforce in research and development
D Percent of gross national product for research and development

Sources: Derived from National Science Board, *Science and Engineering Indicators* (various years), Rescher (1978) and Price (1963).

product devoted to scientific research (US National Science Board, *Annual Reports*). Of course, we have known since the time of Malthus that most forms of exponential growth must eventually come to a halt. No environment can continue to invest such extensive resources in scientific research: otherwise, at some point everyone would be a scientist and a society's entire gross national product would be devoted to scientific research. Nevertheless, in all advanced industrial societies, the percentage of the population and of the GNP devoted to scientific research is continuing to increase, just not exponentially (National Research Council Canada 2005).

To understand these processes, we need to recall Max Planck's *Principle of Increasing Effort*: "with every advance in science, the difficulty of the task is increased; ever larger demands are made on the achievements of researchers, and the need for a suitable division of labor becomes more pressing" (Planck 1949: 376; Rescher 1978: 81). With the expansion of knowledge comes increasing specialization, the development of new subspecialties, and need for additional support staff. There are also increases in new instrumentation, leading to improved methods of measurement, which in turn lead to new fields of specialization and the need for even better instrumentation.

Figure 4 Number of Major Breakthroughs Relative to Scientific Effort



Sources: Derived from National Science Board, *Science and Engineering Indicators* (various years), Rescher (1978) and Price (1963).

When new fields open up, the early investigators often make major breakthroughs: "the pickings are easier." As fields mature, the effort and resources required for significant advances increases continually. This "digging and searching" for significant findings as fields mature and broaden fuels an unending need for even more resources. As a result of this dynamic, the societal resources required to bring about a major discovery tend to increase exponentially. However, the number of major discoveries per annum increases very modestly – if at all. Figure 4 illustrates the dramatic decline in the number of major discoveries relative to the investment society has made in science.

As the demand increases for more financial resources for scientific research, central governments become more involved in funding science and shoulder an increasing percentage of research expenditures, thus altering the institutional environment in which scientific research is embedded. This has several consequences for the structure and culture of the social system of science. First, as central governments increase the proportion of their budgets spent on scientific research, politicians and government bureaucracies become more involved in making decisions about how funding should be allocated. Certain fields of science receive an increasing proportion of investment while other areas are given only scant attention. Meanwhile, scientific communities engage in massive lobbying and public relations campaigns in an effort to influence the decisions of public officials. Second, as the amount of public sector money invested in science rises, governments increase their monitoring and auditing of research organizations in order to enhance research "efficiency and effectiveness" and to prevent fraud. Research organizations – like business firms – increasingly become part of the "audit society." Third, governments acquire a taste for assessing the social benefits of scientific research and express little interest in funding the pursuit of knowledge for its own sake. They support research that promises payoffs "here and now"; in other words, they prefer research with short-term societal benefits rather than high-risk research. Fourth, as central governments become more involved in funding science and making decisions about how the money should be used, research organizations increasingly lose their autonomy. One consequence of these processes is an increasing convergence in the behavior of research organizations, a movement toward greater organizational isomorphism. Researchers tend to gravitate toward scientific areas where there is funding. Since diversity in types of research organizations is associated with organizational autonomy and flexibility as well as scientific breakthroughs, an increase in the strength of the American institutional environment and greater organizational isomorphism pose major problems for the capacity of American research organizations to continue making major breakthroughs.

Finally, the strengthening of the institutional environment of the American system of science is leading to increased commercialization of science. From a theoretical point of view, the strengthening of an institutional environment and an expanding role of the state in funding science do not necessarily lead to the commercialization of science. In the U.S. case, the association between the strengthening institutional environment and the commercialization of science resulted primarily from the fact that the American scientific enterprise has historically been deeply embedded in a highly entrepreneurial culture.

To understand how this process has evolved in the American context, we must first recognize that social systems of science are somewhat bifurcated into public (i.e., communal) knowledge and private knowledge, and each of the two subsystems of knowledge has its own norms, incentives, and behavior. Public knowledge is simply knowledge owned by everyone in common. An example is knowledge published in scientific journals to which everyone has access: the reading of a scientific paper does not diminish its use for the next reader. This is very different from private knowledge, which is a private good not available to all – in other words, if Jake eats his cake, no one else can eat it. If private knowledge is patented or its use acquired by licensure, it is restricted to private use. These two systems of knowledge have their own incentive structures. To most observers it has been relatively easy to understand the pecuniary motives of those who produce private knowledge in the marketplace. But what have been the incentives that motivate those who produce knowledge owned in common by the community?

Sociologists and economists have observed that a major incentive to produce public knowledge has been peer recognition. Historically, societies have bestowed rewards such as medals, prizes, and other forms of esteem on the

Table 3 Public Sector Science in the United States[a]

Property rights of scientific production	Science produced as a public good, belonging to the larger community.
Incentives to produce science	The reward is recognition of priority in discovery. Rewards come in the form of scientific awards, scientific citations, peer group esteem, salary increases.
Methods of funding	Sector funded by patrons, governments, grants, gifts, and contracts. If left to the market, the sector will be underfunded.
Locus of production	Heavy concentration in private non-profit and public sector organizations, although occasionally for-profit organizations produce public goods.
Vulnerability of sector	Sector tends to become bureaucratically funded over time. Funders grow less willing to finance high-risk projects. Research organizations become increasingly large and fragmented, hampering communication across diverse fields. As industrialization increases, an increasing proportion of scientists seek monetary rewards rather than knowledge as an end in itself.
Long-term consequences of public sector science	Highly variable. Some knowledge has few or no effects on society; other knowledge may have societal effects far in excess of the financial resources originally invested. Most major discoveries take many years to have fundamental payoffs, though a few have immediate benefits.

a For discussion of the literature on public knowledge, consult Merton (1973), Dasgupta/David (1994).

discoverer. Such an incentive system has historically generated a great deal of competition among scientists and occasionally intense feuds over whose work deserved priority in being recognized. To facilitate the working of an effective incentive system and to assist in adjudicating priority disputes, the international scientific community has scientific elites who determine what contributions to knowledge are important contributions. Table 3 briefly describes the public science sector in the United States.

While modern societies have had a scientific sector that produces public goods (i.e., public sector science), during the process of modernization, the for-profit sector has also produced science and technology at an accelerating rate. In the for-profit sector, the incentives for research have been primarily monetary in nature. During the past fifty years, the particular process of American industrialization has tended to diminish the proportion of individual scientists pursuing communal obligations and production of public knowledge and to increase the proportion of scientists engaged in the pursuit of pecuniary gain. This process has become one of the most important forces leading to a transformation in the American system of science. Table 4 presents the characteristics of the for-profit science sector in the United States.

Table 4 For-Profit Sector Science in the United States[a]

Property rights of scientific production	Most of the science produced is proprietary in nature. Patents, copyrights, and licensing agreements are widely used for defining and protecting intellectual property rights.
Incentives to produce science	The rewards are primarily monetary in nature.
Methods of funding	Sector predominantly funded by market forces in the private sector. Increasingly, universities and other non-profit organizations have been licensing discoveries made with federal funds and establishing science parks for private firms with strong affiliations to universities.
Locus of production	Historically heavily concentrated in for-profit organizations but in recent years, this sector also has had increasing activity in non-profit and public-sector research organizations.
Vulnerability of sector	The sector is heavily dependent on decision makers who have short-term horizons. As a result, the sector tends to emphasize incremental research designed to maximize profits in the short term.
Long-term consequences of heavy dependence on for-profit sector of science	If the society becomes excessively dependent on this sector for the production of knowledge, there will not be enough new, basic knowledge necessary for high technological and economic growth on the long run.

a For discussion of the literature on the for-profit science sector, see Dasgupta/David (1994).

While the for-profit sector of science has been expanding in the United States throughout the twentieth century, its rate of growth dramatically increased during the past twenty-five years. Ironically, the increasing role of the government in funding science in the United States is leading to a weakening in the development of public, communal knowledge and science. The passage of the Bayh-Dole Act by Congress in 1980 did much to accelerate the expansion of the for-profit sector of science. This act stipulated that intellectual property resulting from federally (i.e., communally) funded research in universities could be patented, with universities and their researchers to be the beneficiaries of resulting royalties. The act stated that universities, as a condition for receiving federal research funds, had an obligation to make a good-faith effort to transfer resulting technological knowledge to the marketplace or to make it available in some other form for use by society. As a result, university linkages with industry increased dramatically. The number of patents issued to American universities tripled in a single decade (1984–1994). Numerous universities established intellectual transfer offices, developed adjacent science parks, and dramatically increased their equity in firms located nearby and elsewhere. In 2000, American universities earned at least $1 billion by conservative estimates, primarily in royalties (Etzkowitz 2002: chap. 10; National Science Board 2004).

Although an abundance of data is available on changes in patenting, the acquisition of patents by universities only represents the tip of the iceberg in the increasing commercialization of science at American research universities. My interviews with senior administrators and scientists in major research universities are consistent with other studies (Cohen et al. 1998; Agrawal/Henderson 2002), which indicate that patents amount to no more than eleven percent of the flow of knowledge with commercial value into the contemporary marketplace. The more important links between American universities and firms have been the joint ventures between firms and individual university scientists, activities by university scientists in creating their own firms, efforts by universities and their affiliated foundations to act as venture capitalists and to become sole or part owners of new business ventures. Of course, a two-way interaction does take place between universities and firms, as firms in a number of sectors have substantially increased their investments in research conducted at universities. In recent years, major American universities have been at the forefront in developing new technologies that have spawned the transformations underlying a number of economic sectors: biotechnology, information technology, software, and computational biology. Because the knowledge created by American universities is so closely linked to these relatively new sectors, it is not surprising that the universities have been so intricately involved in their commercial development.

In a twenty-five year period following the passage of the Bayh-Dole Act, the historical relationship between public sector science and for-profit sector science has been significantly altered, bringing about a transformation in the culture and behavior of American universities. Historically, universities were sites primarily concerned with producing science as a public good, while for-profit firms were primarily engaged in producing science and technology as private goods, although the distinctions between these two types of organizations were never very tidy. While the two types of organizations had somewhat different goals and reward structures, some universities and their faculties were engaged in producing both public and private knowledge, as were also some for-profit organizations. For example, the laboratories of AT&T and IBM had very enviable records for producing important basic scientific discoveries in the form of public science (Rosenberg 1990). In the past twenty-five years, the differences in the behavior of the two types of organizations have considerably narrowed.

There is some evidence that in the short term the increasing commercialization of the American university is contributing to more technological innovations and to higher levels of economic productivity and growth. Clearly, a robust for-profit science sector has been an important stimulus to the American economy. However, sustainable increases in knowledge and technology are necessary in both public sector science and for-profit sector science. No one knows how to define the proper balance between the two sectors, but we have a great deal of evidence suggesting that, on the long run, public sector science will be underfunded should its financing be left to the market. Findings also indicate that the increasing commercialization of science and the bureaucratization of American research universities are discouraging young investigators from conducting high-risk research.[9]

It is extremely difficult to predict what the economic payoff is likely to be from any particular discovery, and for many years there has been considerable debate about the way advances in technology influence the agenda for fundamental and basic science. Historically, a great deal of interaction and co-evolution has occurred in the development of both science and technology. Yet, for long-term economic growth, a sustainable abundance of fundamental or basic knowledge is necessary. Indeed, the consequences of many fundamental advances in basic knowledge were only realized in the marketplace after long periods of time. Many basic scientific discoveries had little economic payoff in the short term, but reaped considerable dividends decades later. No doubt our societies have yet to realize the economic rewards of many other basic discoveries. Of course, the economic significance of a few major, basic biomedical science discoveries was quickly picked up by business firms and soon thereafter began to yield returns in the marketplace (e.g., the Nobel Prizes for Fred Sanger and Walter Gilbert for their work on the sequencing of DNA, for Dan Nathans and Hamilton Smith for their research on the role of restriction enzymes in cutting up DNA, and for Kary Mullis for his development of the polymerase chain reaction).

The realization of economic rewards from fundamental discoveries in the biomedical sciences is a very inefficient and unpredictable process. There is no way of knowing in advance which discoveries will make a significant contribution to the wellbeing of society or when the consequences might be realized. What is clear from the historical record is that high-risk research and fundamental basic research are necessary for the general good of a society on the long run. There is no empirical evidence to suggest that the future wellbeing of societies will be any less dependent on fundamental discoveries and high-risk research than has been the case in the past. As Wolfgang Streeck has often reminded us, institutional environments that provide strong incentives for underinvestment and overconsumption in the short term are likely to result in an undersupply of productive assets in the longer term (Streeck 1992).

As we consider the future of American science, it is helpful to engage in some historical perspective. In the late eighteenth and early nineteenth centuries,

9 These observations became quite obvious during many interviews that I conducted.

France was at the center of the global system of science. Yet by the middle of the nineteenth century, the center had already begun to shift to Germany, which retained its supremacy until the late 1920s. The center then shifted to Britain, which retained its supremacy through WWII. Since then, the United States has been the major center of Western science. The distribution of major prizes and rankings on citation indices make it unmistakably clear that the United States has been the hegemon in world science for at least a half century.

When we reflect retrospectively on these various centers of excellence, it becomes obvious that their decline in performance relative to other countries had already started just as they were thought to be at the height of their superior performance. The elite in these countries were so engaged in celebrating the achievements of their system that they failed to understand that the dynamics, the structure, and the contradictions inherent in their system were leading to its decline. Future analysts engaging in retrospective analysis of American science at the end of the twentieth century are likely to observe a system which by most indicators was performing extraordinarily well. Yet in retrospect, they are likely to note that the increasing organizational isomorphism both within and across its research organizations, combined with the increasing commercialization of science, had begun to impose fundamental limits on the ability of the American system to sustain its level of excellence.

References

Agrawal, Ajay/Rebecca Henderson, 2002: Putting Patents in Context: Exploring Knowledge Transfer from MIT. In: *Management Science* 48, 44–60.

Astley, W. Graham, 1985: The Two Ecologies: Population and Community Perspectives on Organizational Evolution. In: *Administrative Science Quarterly* 30, 224–241.

Ben-David, Joseph, 1977: *Centers of Learning: Britain, France, Germany, United States*. New York: McGraw Hill.

Cohen, Wesley, et al., 1998: Industry and the Academy: Uneasy Partners in the Cause of Technological Advance. In: Roger Noll (ed.), *Challenges to the Research University*. Washington, DC: Brookings Institution.

Crouch, Colin, et al., 2005: Dialogue on 'Institutional Complementarity and Political Economy.' In: *Socio-Economic Review* 3, 359–382.

Dasgupta, Partha/Paul A. David, 1994: Toward a New Economics of Science. In: *Research Policy* 23, 487–521.

DiMaggio, Paul/Walter W. Powell, 1983: The Iron Cage Revisited: Institutional Isomorphism and Collective Rationality in Organizational Fields. In: *American Sociological Review* 48, 147–160.

Etzkowitz, Henry, 2002: *MIT and the Rise of Entrepreneurial Science*. London: Routledge.

Hage, Jerald/J. Rogers Hollingsworth, 2000: Idea Innovation Networks: A Strategy for Integrating Organizational and Institutional Analysis. In: *Organization Studies* 21, 971–1004.

Hodgson, Geoffrey, 2003: The Mystery of Routine: The Darwinian Destiny of an Evolutionary Theory of Economic Change. In: *Revue Economique* 34, 355–384.

Hollingsworth, J. Rogers, 2004: Institutionalizing Excellence in Biomedical Research: The Case of The Rockefeller University. In: Darwin H. Stapleton (ed.), *Creating a Tradition of Biomedical Research: Contributions to the History of The Rockefeller University*. New York: Rockefeller University Press, 17–63.

Hollingsworth, J. Rogers/Robert Boyer (eds.), 1997: *Contemporary Capitalism: The Embeddedness of Institutions*. Cambridge: Cambridge University Press.

Hollingsworth, J. Rogers/Ellen Jane Hollingsworth, 2000: Major Discoveries and Biomedical Research Organizations: Perspectives on Interdisciplinarity, Nurturing Leadership, and Integrated Structure and Cultures. In: Peter Weingart/Nico Stehr (eds.), *Practising Interdisciplinarity*. Toronto: University of Toronto Press, 215–244.

Hollingsworth, J. Rogers/Ellen Jane Hollingsworth/Jerald Hage (eds.), 2006: *The Search for Excellence: Organizations, Institutions, and Major Discoveries in Biomedical Science*. New York: Cambridge University Press (forthcoming).

Kuhn, Thomas S., 1962: *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press.

Mayr, Ernst, 2001: *What Evolution Is*. New York: Basic Books.

McKelvey, Bill, 1982: *Organizational Systematics: Taxonomy, Evolution, Classification*. Berkeley: University of California Press.

Merton, Robert K., 1973: *The Sociology of Science: Theoretical and Empirical Investigations*. Chicago: University of Chicago Press.

National Research Council Canada, 2005: *Looking Forward: S&T for the 21st Century – Foresight Consolidation Report, NRC Renewal Project*. August 2005. <www.nrc-cnrc.gc.ca/docs/NRC-Foresight_Consolidation_Report_e.pdf>

National Science Board, 2004: *Science and Engineering Indicators 2004*. Arlington, VA: National Science Foundation.

Planck, Max, 1949: *Vorträge und Erinnerungen*, 5th Edition. Stuttgart: S. Hirzel.

Price, Derek J. de Solla, 1963: *Little Science, Big Science*. New York: Columbia University Press.

Rescher, Nicolas, 1978: *Scientific Progress*. Pittsburgh, PA: University of Pittsburgh Press.

Rosenberg, Nathan, 1990: Why Do Companies Do Basic Research with Their Own Money? In: *Research Policy* 19, 165–174.

Stinchcombe, Arthur, 1965: Social Structure and Organizations. In: James March (ed.), *Handbook of Organizations*. Chicago: Rand McNally, 153–193.

Streeck, Wolfgang, 1992: *Social Institutions and Economic Performance: Studies of Industrial Relations in Advanced Capitalist Economies*. London: Sage.