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The Knowledge Filter, Entrepreneurship, and Economic Growth

by

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THE KNOWLEDGE FILTER, ENTREPRENEURSHIP, AND ECONOMIC GROWTH

May 2007

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Abstract

This paper explores the relationship between knowledge creation, entrepreneurship, and economic growth in the United States over the last 150 years. According to the “new growth theory,” investments in knowledge and human capital generate economic growth via spillovers of knowledge. But the theory does not explain how or why spillovers occur, or why large investments in R&D do not always result in economic growth. What is missing is “the knowledge filter” - the distinction between general knowledge and economically useful knowledge. Also missing is a mechanism (such as entrepreneurship) converting economically relevant knowledge into economic activity. This paper shows that the unprecedented increase in R&D spending in the United States during and after World War II was converted into economic activity via incumbent firms in the early postwar period and increasingly via new ventures in the last few decades.

JEL-classification: O14, O17, O30, N90

Keywords: knowledge, economic growth, entrepreneurship, spillovers, history

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THE KNOWLEDGE FILTER, ENTREPRENEURSHIP, AND ECONOMIC GROWTH*

INTRODUCTION

According to the so-called new growth theory (Romer (1986, 1990), Lucas (1988), and others) investments in knowledge and human capital generate economic growth not only directly by making other inputs more productive but also indirectly via spillovers of knowledge. But the theory does not explain how or why spillovers occur, nor why large investments in R&D do not always result in rapid economic growth. What is missing is a distinction between general knowledge and knowledge that is economically useful (following Arrow 1962). Also missing is specification of a mechanism converting economically relevant knowledge into economic activity. These distinctions are important for understanding (1) why large investments in R&D (such as in Japan and Sweden) do not necessarily result in high economic growth, (2) why entrepreneurial activity plays a more important role in some countries (e.g., the United States) than in others (Europe and Japan), and (3) why these relationships shift over time. The underlying question is: why doesn't new knowledge always result in (new) economic activity?

In a series of papers (Acs *et al.*, 2004, 2005a and b) we have developed a model that distinguishes between knowledge and economic knowledge by introducing the notion of a knowledge filter that prevents knowledge from becoming economically useful. We have also identified entrepreneurship as a mechanism (in addition to

* Comments by Richard Baznik and the discussant at the DRUID conference in Copenhagen in June, 2006, on earlier versions of this paper are gratefully acknowledged.

incumbent firms) that converts economic knowledge (via knowledge spillovers) into economic growth.

The purpose of this paper is to explore the nature of the knowledge filter and to explain how it influences innovation and economic growth. We focus primarily on the United States, occasionally comparing the U.S. experience with that elsewhere.

The paper is organized as follows. We begin with a conceptual overview of the knowledge creation system and the role of filters or obstacles that prevent knowledge from resulting in economic activity. We then present an historical overview of the organization of academic and industrial research in the United States and how the knowledge filter has waxed and waned over the years. We start with a discussion of how the industrial revolution was based in part on turning knowledge into economically useful knowledge and how university education and research in the United States became practically and vocationally oriented (in comparison with European universities), partly through the land-grant universities established in the mid- to late 19th century. In the early part of the 20th century, corporate research and development labs began to emerge as major vehicles of basic industrial research. Virtually all of the funded research prior to World War II was conducted in corporate or federal labs. In conjunction with a rapidly increasing share of the population with a college education, this made for high absorptive capacity on the part of industry and, as a result, a “thin” knowledge filter. In subsequent sections we discuss the emergence of the research university, the dramatic increase in research and development spending, and the shift of basic research toward the universities, especially during and following World War II. During the 1960s and 1970s, this led to a thickening of the knowledge filter in the form of an increasing need to

“translate” basic (academic) research into economic activity. New firms have increasingly become the vehicle to translate research into growth; this can be seen in the greater role of small business and entrepreneurship from the 1970s onward. Meanwhile, the R&D of large incumbent firms has become more applied and oriented toward building absorptive capacity rather than pushing out the knowledge frontier. We conclude with a discussion of the implications for innovation, entrepreneurship, and economic growth.

THE KNOWLEDGE CREATION SYSTEM

A schematic picture of the knowledge creation system is presented in Figure 1. There are two main types of research: academic and industrial. The former is primarily basic and is carried out in universities or research institutes, while industrial R&D primarily involves applied research or development work and is carried out in industrial firms or government laboratories.¹ In the United States, basic R&D currently makes up slightly less than 20 percent of the total R&D, while applied research makes up a little more than 20 percent. The remaining 60 percent is development R&D (NSF, 2006a). A large part of academic research and a substantial part of industrial R&D has no direct commercial value (i.e., is not economically useful).

¹ The Frascati Manual defines *basic research* as “experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular use in view. *Applied research* is also original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific practical aim or objective. Experimental development is systematic work, drawing on existing knowledge gained from research and/or practical experience, which is directed to producing new materials, products, or devices, to installing new processes, systems and services, or to improving substantially those already produced or installed” (OECD, 2002, p. 30).

The part of industrial R&D (in the lower part of Figure 1) that is judged to have potential economic value (i.e., passes the economic value filter) can be turned into intellectual property to be subsequently commercialized (if it turns out to have sufficient commercial value), or it can be indirectly commercialized by increasing the absorptive capacity or knowledge base of the company. Commercialization can be accomplished via expansion of the activities (new or improved goods and services) in existing firms – the main vehicle – or via spin-off to new entities, or via licensing to other firms.

Most academic research (in the upper part of Figure 1) is basic and has no direct economic value. There are two types of research output that does have potential economic value. The most important is in the form of knowledge that graduating students take with them into the labor market, i.e., educated labor (human capital, including skilled researchers). Another important output is research that is judged to have potential economic value, i.e., it passes the institutional filter. The first step in the commercialization process is an invention disclosure. The researcher/inventor and/or the technology transfer organization of the employer (university) decides whether or not to apply for a patent. If this results in a patent application and if a patent is approved, the invention passes the economic value filter and becomes intellectual property that can be commercialized via licensing to an existing firm or via start-up of a new firm.²

What constitutes the knowledge filter? The knowledge filter is what separates knowledge from economically useful knowledge (Arrow 1962). The basic knowledge

² Only about half of the invention disclosures in U.S. universities result in patent applications; half of the applications result in patents; only 1/3 of patents are licensed, and only 10-20 % of licenses yield significant income (Carlsson and Fridh, 2002, p. 231). In other words, only 1 or 2 percent of the inventions are successful in reaching the market and yielding income.

produced in academia may be in areas (such as the humanities) that have little or no economic value (even though it may have significant human value). The research may not be advanced enough to be on the knowledge frontier, or it may not be sufficiently broad, deep, or systematic to be useful in applied research or development that can lead to commercialization. In practical terms, the allocation of funding of academic research in the United States may be viewed as reflecting the perceived economic value of research in various disciplines. In 2004, the life sciences received nearly 60 % of all R&D funding at U.S. universities and colleges, all other sciences (including social sciences) about 25 %, and engineering the remaining 15 % (NSF, 2006a).

The knowledge filter is the sum of the barriers to converting research into commercialized knowledge. The first component of the knowledge filter as far as academic research is concerned may be referred to as the institutional filter. It consists of organizational barriers, university policies, attitudes among faculty and university administrators against commercialization of research, and lack of incentives to pursue commercialization. The main output of academic research is often highly skilled labor. The higher the barriers to commercialization of research, the greater is the share of research dissemination via skilled labor.

The second and third components of the academic knowledge filter are the economic and commercial value filters which reflect the capability to convert invention disclosures into intellectual property (primarily in the form of patents) and then to commercialize the intellectual property via licenses and start-ups.

There are similar filters for industrial R&D reflecting the difficulty in business organizations to convert research into intellectual property and to commercialize new products. The greater are the obstacles to commercialization of research, the thicker is the knowledge filter.

The research efforts of academic institutions have increased enormously over time, with varying economic impact. On the whole, U.S. universities have been much more successful in commercializing research than their foreign counterparts. But external funding of academic research is a relatively recent phenomenon; the research university as we know it today did not emerge in the United States until around World War II. It is only in the last few decades that basic academic research has begun to play an important role in the economy. We turn now to a brief historical overview.

HISTORICAL OVERVIEW OF ACADEMIC AND INDUSTRIAL RESEARCH AND THE KNOWLEDGE FILTER

Universities and Their Role in Knowledge Creation

Universities began to arise in Europe during the Middle Ages.³ They developed out of monastery and cathedral schools, attended by adolescents and taught by monks and priests. One of the first was in Bologna, established in 1088, followed by Paris (1160), Modena (1175), and Oxford (1190). The curriculum consisted of the art of reading and writing, focusing on the Bible and the Latin and Greek classics, rhetoric, and logic. Knowledge meant logic, grammar, and rhetoric; it did not mean ability to do, or utility.

³ There were earlier precedents in China, India, and the Middle East.

The role of the universities was to collect, codify, and teach general knowledge. Utility or economic knowledge was not thought of as knowledge but rather as skill – the Greek word *téchne*. The only way to learn *téchne* or skill was through apprenticeship and experience.

The establishment of the first engineering schools in the mid-18th century represents the beginning of codification of economically useful knowledge. The French *École des Ponts et Chaussées* was the first engineering school, founded in 1747. It was followed around 1770 in Germany by the first school of agriculture and in 1776 by the first school of mining. The first technical university, *École Polytechnique* in France, was established in 1794. Meanwhile in Britain the application of patents shifted from establishing monopolies to enrich royal favorites (first granted in the mid-15th century) to patents being granted to encourage the application of knowledge to tools, products, and processes, and to reward inventors, provided that they published their inventions.

(Drucker, 1998, pp. 18-21)

None of the technical schools of the eighteenth century aimed at producing *new* knowledge... None even talked of the application of science to tools, processes and products, that is, to technology. This idea had to wait for another hundred years until 1849 or so, when a German chemist, Justus Liebig (1803-1873), applied science to invent first, artificial fertilizers and then a way to preserve animal protein, the meat extract. What the early technical schools... did was, however, more important perhaps. They brought together, codified and published the *téchne*, the craft mystery, as it had been developed over millennia. They converted experience into knowledge, apprenticeship into textbook, secrecy into methodology, doing into applied knowledge. These are the essentials of what we have come to call the “Industrial Revolution,” i.e. the transformation by technology of society and civilization worldwide. (Drucker, 1998, p. 21)

The first university in the United States was Harvard College, founded in 1636 and established in the tradition of European universities. Seven of the nine colleges

founded in the colonial era (all of which were private)⁴ were oriented to a classical curriculum in preparation for civic leadership or ministry. After independence, private and public universities were established in parallel. The University of Georgia (1785) was the first state university. After the Civil War, the Morrill Land-Grant College Act (1862) led to the establishment of universities in every state. Unlike most private universities, these state universities and colleges were charged with public service obligations in agricultural experimentation and extension services,⁵ industrial training, teacher education, home economics, public health, and veterinary medicine. (Graham and Diamond, 1997, p. 18) Some of the land-grant universities were private (e.g., M.I.T.). One of their main features was a strong practical/vocational orientation in both education and research. While the emphasis was on teaching branches of learning related to agriculture and the mechanical arts in addition to the liberal arts, there was also research. The Morrill Act also stimulated engineering education. The number of engineering schools increased from six to 70 within a decade, and the number of engineering graduates grew from 100 in 1870 to 4,300 in 1914 (Nelson & Wright, 1992, p. 1942). Since the research agenda was driven primarily by the needs of the rapidly expanding economy and largely involved applied research, this made for a thin knowledge filter. The new knowledge was easily converted into economic activity.

Meanwhile in Europe, the tradition of higher education continued to focus on teaching, but the advent of Humboldt University in Berlin in 1809 represented a new approach, focused on research. This was the first research university; adherence to

⁴ Two of these, the College of William & Mary and Queen's College (now Rutgers) were later converted to public universities.

⁵ After the Hatch Act of 1887 (Nelson & Wright, 1992, p. 1942).

scientific and scholarly discipline emerged as preeminent, not worldly application of knowledge.

As a result of the different origins of U.S. colleges and universities with respect to both ownership and mission, the American system of higher education has been decentralized and pluralistic as well as competitive from the very beginning, in clear contrast to Europe:

By the late nineteenth and early twentieth centuries, higher education systems in Europe were typically centralized under a national ministry of education. As a consequence, higher education policy was essentially government policy. Like most public bureaucracies, Europe's state-dominated systems of higher education were organized hierarchically by function. Competition was minimized by bureaucratic boundaries, much as it was in ministries of justice, war, or public health. Teaching faculty were typically civil servants. The European university was the training ground for the middle and professional classes, and for this reason, attendance was confined to a small, closely screened cadre of academically talented students who sought advanced professional and vocational training rather than general education in the liberal arts, the goal of American college students... Even though chair professors dominated their institutes, the basic decisions about university budgets, student admissions, and academic programs were made by central ministry officials, not by campus academic officers. The centralized system of European higher education achieved organizational rationality and bureaucratic efficiency at the expense of competition and innovation (Graham and Diamond, 1997, pp. 12-13).

In European countries, ministries of education have typically paid the costs and set the agenda for the university. As a result, European universities have had limited authority to manage their own size and shape, their entry or exit requirements, and their broad character and function. (*ibid.*, p. 23) By contrast, American private universities are typically governed by a board of non-resident, non-academic trustees, led by a powerful president, and independent of control or support by the state.

Almost without exception, American universities were built around a large, core college of arts and sciences, organized into discipline-based departments in which faculty appointments and tenure were based. This common organizational form

traced its origin to the colonial colleges and, by the nineteenth century, to the peculiar need for American undergraduate education to fill the void left by a democratic system of public secondary schools that valued high graduation rates over demanding standards. The *raison d'être* of “the college” was thus to provide baccalaureate education in the liberal arts and sciences for residential undergraduates, while the graduate school offered masters and doctoral degrees, and separate schools offered professional degrees...

When the German model of the research university was imported to the United States by way of Johns Hopkins late in the nineteenth century, it was admired and emulated. But it was also quickly Americanized. The research and graduate orientation of the German model took a prominent and permanent place in the hierarchy of American academic prestige. But the American graduate school was superimposed on the colleges of arts and sciences, with their undergraduate-centered departmental organization. By the early twentieth century even Johns Hopkins looked more like Yale, or like the University of North Carolina, than like von Humboldt’s model in Berlin. (Graham and Diamond, 1997, p. 19)

The decentralized and pluralistic American system allowed for much faster expansion than that in Europe without requiring structural change. In 1910, about 330,000 students were studying at almost one thousand colleges and universities in the United States (whose population was 92 million), while there were only 14,000 students in sixteen universities in France (with a population of 39 million). This represented about 4 % of the college-age population in the U.S. vs. about 0.5 % in France. In most European countries (including Britain), college enrollments did not exceed 5 percent of the college-age group until after World War II (*op. cit.*, p. 15). By 1940, the percentage of college-age Americans attending institutions of higher education was three times higher than the European average (roughly 12 % in the U.S. versus 4 % in Europe). (*op. cit.*, p. 24)

The expansion of the U.S. system of higher education allowed it to cater not only to a rapidly growing population but also to increasing percentages of each cohort demanding higher education. This set the U.S. system apart from its European

competitors. It contributed importantly to the creation of a relatively highly educated industrial labor force, i.e., a relatively high capacity to absorb new technology. And this contributed significantly to the rising economic power and competitiveness of the United States. But it needs to be kept in mind that until World War II, the main function of U.S. universities was primarily as repositories and disseminators of knowledge rather than as creators of knowledge.

To a considerable extent this was because of the weakness of U.S. academic institutions in research. The emphasis was clearly on the quantity of students, not the quality of research. Even as late as during the first half of the 1920s Americans often traveled to Europe to learn, and when European scientists traveled to the United States, they did so primarily to teach. An aspiring student seeking the best available academic education in scientific disciplines such as physics or chemistry would have been well advised to study in Germany, Britain, or France (Nelson & Wright, 1992, p. 1941). But this situation changed markedly by the end of the decade as American scientists reached the scientific frontier. The U.S. attained parity with the leading Europeans well before events in Europe forced the intellectual migration of the 1930s (Geiger, 1986, pp. 233-234). However, external research funding was still quite small. During the interwar period, U.S. academic research was funded primarily by philanthropic foundations (such as the Rockefeller and Carnegie Foundations) and large corporations (e.g., Du Pont, General Electric, Borden, and Lilly). The federal government was not involved in funding academic research at this time. The total value of foundation grants to academic institutions was only on the order of \$50 million in 1931 and then fell dramatically as the depression deepened. It rose again in the late 1930s but attained only \$40 million in

1940.⁶ The externally funded academic research was also concentrated in just a handful of institutions. Among sixteen preeminent universities⁷ only six spent more than \$2 million annually (from all sources, including internal) in the late 1930s, and four spent less than \$1 million. Eleven of these were private institutions (Graham & Diamond, 1997, p. 28). Most research grants were small and made to individuals rather than to institutes or schools; there were few if any institutional grants. Research funding was not on the agenda of university presidents.

Thus, although both American universities and American industry had increased their capacities for scientific research during the interwar period, the best among them having reached parity with Europe's best in most areas by the early 1930s, the total research effort was still small compared to what was to come during and after World War II. Most of the limited basic research that was done was carried out in industrial and government labs. Industrial expenditures for basic and applied research had reached \$200 million in 1939, up from just over \$100 million a decade earlier and \$30 million at the start of the 1920s (Geiger, 1993, p. 4). Expenditures for research in government and industry, overwhelmingly applied in character, were ten times university expenditures for basic research in 1940 (*op. cit.*, p. 14). As a result, a large part of the new knowledge created (though limited in scope) was directly economically useful and therefore relatively easily transformed into economic activity.

⁶ The fact that external research funding was so limited does not mean that no research was conducted, only that it was focused on areas that did not require expensive equipment or large laboratories. "Big science" projects in science, engineering, and medicine were new phenomena that did not come about until during and after World War II.

⁷ These sixteen were UC Berkeley, Chicago, the California Institute of Technology (Caltech), Columbia, Cornell, Harvard, Illinois, Johns Hopkins, MIT, Michigan, Minnesota, Pennsylvania, Princeton, Stanford, Wisconsin, and Yale.

By 1945 there were 641 public institutions in 48 state systems and about 1,100 private institutions with a combined total enrollment of about 1.6 million students evenly split between public and private institutions. Both the public and the private institutions varied widely in purpose, size, and quality. Even though the number of public institutions more than doubled between 1950 and 1988 (from 641 to 1,548), the private institutions were still in a majority. The strongest growth was in public two-year community colleges (Graham and Diamond, 1997, pp. 15-16; Snyder, 1993).

Early 20th century: the emergence of corporate R&D labs

As mentioned already, the research conducted in American and European universities in the earlier part of the 20th century was fairly limited. But as the number of universities grew in the United States – particularly in the first decade after the Civil War and in the 1890s when many land-grant universities were established – and with it the number of graduates, the skills of the industrial labor force increased. New science-based industries emerged that constituted the core of the “Second Industrial Revolution” – those relying on chemistry, electricity, and the internal combustion engine. But “relatively little of the American performance during this era was based in science, nor even on advanced technical education. American technology was practical, shop-floor oriented, built on experience. The level of advanced training in German industry was substantially higher.” (Nelson & Wright, 1992, p. 1938) The new industries needed new knowledge, but the universities did not possess the specialized knowledge, equipment, and organization that was required. Instead, a new mechanism emerged in the form of industrial laboratories.

During the latter half of the 19th century a number of industrial labs were established in the United States. There were at least 139 by the turn of the century (Mowery, 1981, cited in Rosenberg, 1985, p. 51). The earliest industrial labs did not perform activities that could be regarded as research; they were set up to apply existing knowledge, not to make new discoveries. They were organized to engage in a variety of routine and elementary tasks such as testing and measuring in the production process, assuring quality control, standardizing both product and process, and meeting the precise specifications of customers (Chandler, 1985, p. 53). But as Rosenberg points out, this development was linked to the expansion of higher education in the United States:

“The growing utilization of scientific knowledge and methodology in industry was vastly accelerated by an expanding pool of technically trained personnel – especially engineers. Associated with this expansion was the growth in the number of engineering schools, engineering programs, and the engineering subspecialties in the second half of the nineteenth century.... But it is essential... to realize that it was the larger body of scientific knowledge, and not merely frontier science, that was relevant to the needs of an expanding industrial establishment.” (Rosenberg, 1985, p. 24)

The links between *science* and industry - the emergence of new bodies of scientific knowledge that were subsequently applied to industry - were established somewhat later in a second stage of development in the form of corporate R&D laboratories. The expansion of higher education coincided with the establishment of such laboratories.

U.S. universities played an important role in the creation of such laboratories, via collaborative research and consulting, and in developing expanded research capabilities over time, in addition to serving as the launching pad for the careers of individuals who found employment in private firm laboratories. There is also evidence of influence in the

opposite direction, from firms to universities. By providing both financial support for university research laboratories and a market for future trained labor, firms supported the growth of scientific capabilities at local universities. (MacGarvie and Furman, 2005, pp. 4-5)

Critical to this second stage [the corporate R&D labs] was a separation of the testing, standardizing, and quality control functions from those of product and process development. This separation involved, first, the creation of a laboratory physically separate and usually geographically distant from the factory or factories of the enterprise. Of even more importance, it called for the creation of a separate, specialized organization to exploit the laboratory's activities. This organization usually took the form of a department separate from those responsible for production, distribution, and purchasing activities of the enterprise. The new department's objective was to define programs for the laboratory by monitoring both market and technological opportunities. Its most critical task was to integrate the activities of the research personnel with those of university professors working closer to the sources of scientific knowledge and with those of managers in the company's design, manufacturing, and marketing offices. (Chandler, 1985, p. 54)

The primary function of this new type of department – the *corporate research and development* laboratory – was not basic research but rather the commercial development of products and processes. Shortly after the turn of the century, a handful of relatively new - but still big - businesses made a marriage between science and business by creating such laboratories. The first corporate R&D lab was established by Du Pont in 1902. It was soon followed by the leaders in the electrical, chemical, photographic, and telecommunications industries. These firms had one thing in common: They were based on technologies that had emerged in one way or another from scientific discoveries or developments and were particularly susceptible to significant, further improvement through a scientific approach to problem solving. As a result, science became a part of corporate strategy (Hounshell& Smith, 1988, p. 1). Another result was that a much larger

fraction of business-supported research was conducted *within* firms in the U.S. compared with Europe where industry-wide associations or other arrangements played an important role (Rosenberg, 1985, p. 24).

But the modern corporate research and development laboratory did not emerge full blown from the minds of executives at such firms as Du Pont, General Electric, Eastman Kodak, and American Telephone and Telegraph. The first organized industrial laboratories had appeared in Germany in the 1870s, in firms that sought to commercialize inventions based on new breakthroughs in organic chemistry (MacGarvie and Furman, 2005, p. 9). What distinguished these German corporate chemical laboratories and set them apart from other approaches to innovation was that modern corporate chemical research called for massive scientific teamwork rather than the efforts of individual chemists. It also set the international pattern for the conduct of research in the chemical-related industries: most of it has been in-house at the firms, although some has been outsourced to universities. Also, once researchers had uncovered the mechanisms of reactions, they could then pursue the invention of new dyes in a highly regular, systematic way.

The number of routine experiments that had to be conducted to find a single promising color was large. When such a color was discovered, it was sent to the dye-testing division, where it was subjected to a battery of tests to indicate whether and under what conditions it would tint anyone of the common fibers, or such other items as wood, paper, leather, fur, or straw. Then each item successfully tinted was subjected to several agents of destruction to determine fastness. Of 2,378 colors produced and tested [by Bayer] in the year 1896, only 37 reached the market. This tedious, meticulous experimentation, in which a thousand little facts were wrenched from nature through coordinated massed assault, admirably illustrates the method and spirit introduced into scientific inquiry by the rising industrial laboratory of the late nineteenth century. (John J. Beer, quoted in Hounshell & Smith, p. 5)

As a result of these developments, while an increasing share of American industrial production was based on new knowledge in the form of scientific discoveries, the supporting research activity took place primarily in corporate R&D labs, not in universities.

World War II and the Emergence of the Research University

The research university in the United States is largely a postwar phenomenon, but as indicated above, its foundations were laid long before. It was patterned after the German model (von Humboldt's University of Berlin), but in contrast to its European predecessor it emerged into a "decentralized, pluralistic, and intensely competitive academic marketplace fueled by federal research dollars" (Graham & Diamond, 1997, p. 2). Competitive pressures forced the American research universities to change much more quickly than did the sheltered public universities elsewhere.

The war effort led to an enormous scaling up of U.S. research to an unprecedented level. For example, the Army Corps of Engineers alone spent \$2 billion on the atomic bomb and the Radiation Laboratory at MIT expended \$1.5 billion for radar systems (Geiger, 1993, p. 9). This should be compared with total industrial R&D expenditures on the order of \$200 million just before World War II. The increased research was guided by military needs and involved both basic research and its immediate application and development in the form of military goods and services (which translated directly into economic activity as these goods had to be paid for by the federal government).

During World War II the U.S. government harnessed the talent of the top scientists and engineers at these [top] universities, not - as had been done in World War I - by inducting them into uniformed service in war-related bureaucracies but by developing a new contract and grant system under the

leadership of civilian scientific elites. The success story of the wartime Office of Scientific Research and Development (OSRD) is well known. To lead the mobilization of scientific manpower, President Roosevelt in 1940 summoned Vannevar Bush, former dean of engineering at MIT and, since 1938, president of the Carnegie Institution of Washington. Bush in turn brought in a powerful trio of senior associates: Karl T. Compton, president of MIT; James B. Conant, president of Harvard; and Frank B. Jewett, board chairman of Bell Telephone Laboratories and president of the National Academy of Sciences. A formidable group, they represented the major sectors of science and technology outside of government. The OSRD developed an intense and intimate model of collaboration between Washington and the nation's leading universities. The wartime development of radar, the proximity fuse, penicillin, DDT, the computer, jet propulsion, and the climactic trump card, the atomic bomb, brought enormous prestige to the scientific community. From the development of radar at MIT, through the control of nuclear fission at the University of Chicago, to the University of California's secret operations at Los Alamos, scientific brilliance in the national interest was associated with the great universities. (Graham & Diamond, 1997, p. 28)

Thus, the magnitude, nature, and locus of U.S. research and development changed dramatically in conjunction with World War II, necessitated by the war effort and funded by the federal government. Prior to the war, the federal government had almost no role in funding academic research. Its research funding went to government (intramural) labs and to defense contractors. Only government and industrial labs had the necessary resources to carry out large-scale, systematic, programmatic research. The sheer scale of the war-time research effort required the engagement of academic researchers as well. This, in turn, required massive investments in building up the research infrastructure of the universities.

Impressive as the federal effort was to mobilize the nation's scientific resources to develop the means necessary to win the war, it is a story not only about research funding, brilliant scientists, and organization at the federal level. It is also a story about the internal culture and organization of the universities and about the relations between the

universities and their external environment, particularly industry.⁸ Granted that academic research in the United States was highly concentrated to a few elite institutions prior to World War II, had these elite universities not been ready to take up the challenge, it is unlikely that their response would have been as rapid and strong as it was. As a result of changes in its internal organization and incentive system during the 1930s, MIT was in a leading position; it is no accident that Vannevar Bush was picked by President Roosevelt to head up the wartime research effort.

As a private land-grant university, MIT had stood virtually alone as a university that embraced rather than shunned industry.

From its start MIT developed close ties with technology-based industrialists, like Edison and Alexander Graham Bell, then later with its illustrious alumnus Alfred P. Sloan, during his pioneering years at General Motors, also with close ties to the growing petroleum industry. In the 1930s, MIT generated The Technology Plan, to link industry with MIT in what became the first and is still the largest university-industry collaborative, the MIT Industrial Liaison Program (Roberts, 1991, p. 33).

MIT's involvement with industry was not confined to established companies, however:

The traditions at MIT of involvement with industry had long since legitimized active consulting by faculty about one day per week, and more impressive for its time had approved faculty part-time efforts in forming and building their own companies, a practice still questioned at many universities. Faculty entrepreneurship, carried out over the years with continuing and occasionally heightened reservations about potential conflict of interest, was generally extended to the research staff as well, who were thereby enabled to 'moonlight' while being 'full-time' employees of MIT labs and departments. The result is that approximately half of all MIT spin-off enterprises, including essentially all faculty-initiated companies and many staff-founded firms, are

⁸ During the interwar period the output of trained professionals was clearly more important than the research carried out in academic institutions: "In 1919... MIT launched its Cooperative Course in electrical engineering, a program that divided the students' time between courses at the Institute and at General Electric, which hired one-half of the students after graduation. The program was later joined by AT&T, Bell Labs, Western Electric, and other firms." (Nelson & Wright, p. 1949, quoting Noble, 1977, p. 192)

started on a part-time basis, smoothing the way for many entrepreneurs to ‘test the waters’ of high-technology entrepreneurship before making a full plunge (Roberts, 1991, p. 34).

In his role as head of the ORSD, Bush not only spearheaded the mobilization of the nation’s science research capabilities; he also revolutionized the relationship between science and government by channeling the funding to universities rather than to government labs, despite the fact that it involved military research (Roberts, 1991, pp. 13-14). In World War I, scientists had been recruited to government labs. The new way of organizing the war effort made it possible to tap into existing research facilities and capabilities and thus scale up the research much more quickly than would have been the case otherwise. It also suddenly established the federal government as *the* major source of funding for basic research – something that had not been the case until then.

Another important step was an institutional change in the organization of academic research. In order to accommodate both the academic requirement of education and research for the common good (i.e., via publication) on one hand and the need to protect the confidentiality of military research on the other, it was necessary to find a new way to organize the research. The solution was to set up independent laboratories such as the Draper and Lincoln labs, both organized by MIT faculty who could then divide their time between the normal academic activities and the defense-related research.

Yet another innovation associated with MIT was that in the immediate postwar years MIT president Compton pioneered efforts toward commercialization of new technology, including military developments. Among other things he helped to create the first institutionalized venture capital fund, American Research and Development (ARD), set up in 1946. It was largely Compton’s brainchild. He became a board member, along

with three MIT department heads. ARD's first several investments were in MIT developments, and some of the emerging companies were initially housed at MIT (Roberts, 1991, pp. 33-34). Thus was established another crucial link connecting knowledge creation and commercialization, keeping the knowledge filter as clean as possible. Other universities eventually followed suit. However, in the early postwar years it is clear that the vast majority of research funding went to defense contractors, not universities, and that the bulk of commercialization of new technology took place via incumbent firms rather than via spillovers picked up by new firms.

Postwar Developments: 1945-1965

The impact of World War II on knowledge creation in the United States was four-fold: (1) There was a tremendous increase in R&D spending. (2) The federal government (particularly the Department of Defense) became by far the dominant provider of research funding. (3) The primary thrust was toward systematic, programmatic research. (4) The enrollment in higher education rose dramatically as a result of the so-called G.I. Bill.

The aftermath of World War II involved a tremendous increase of the role of the federal government not only in research but also in funding of higher education. The G.I. Bill, signed into law by President Roosevelt in 1944, was designed to provide educational opportunities to returning war veterans. The U.S. system of higher education expanded rapidly and contributed significantly to increasing capacity in the society to absorb new technology, thereby contributing indirectly to economic growth. The number of colleges increased dramatically. Whereas there were 18 new colleges started annually between

1861 and 1943, the number rose to 25 in 1944-1959 and 50 between 1960 and 1979 (Adams, 2000). The total enrollment in higher education went from 1.5 million (9.1 % of the 18-24-year old cohort) in 1939-40 to 2.4 million (15 %) in 1949 (Snyder, 1993), more than a 50 % increase. By the early 1950s, approximately 8 million veterans had received educational benefits. The GI Bill also brought to the university campuses a population of students – older, more oriented to work than to traditional college-age pursuits, and ultimately more entrepreneurial – different from the pre-war campus crowd.

The R&D initiated during the war was continued after the war. There was a huge increase in total R&D spending from the early 1950s to the mid-1960s, mostly due to a sharp increase in federal R&D spending. R&D expenditures as a share of GDP more than doubled, rising from 1.4 % in the early 1950s to 2.9 % in 1964. See Figure 2. Nearly 80 % of federal R&D funding came from the Department of Defense and NASA. More than half of this defense-related R&D spending was intramural (i.e., carried out within federal agencies), and most of the rest was carried out by industry; less than 5 % was carried out by academic and nonprofit institutions. While modest as a fraction of total U.S. R&D, the funding for academic research represented a major increase in R&D funding for universities. It was the beginning of a long-term shift toward more academic research in the national R&D system. In these early postwar years, less than 2 % of the DoD R&D spending involved basic research, while about 1/3 of NASA's R&D spending was for basic research. By far the largest component of the overall R&D spending involved applied work that was converted very rapidly into economic activity.

When demobilization after the war closed down the OSRD, national political leaders agreed that the government-university collaboration should continue. The

question now became how to organize and institutionalize the nation's research effort. A deep split developed, however, over its structure and control.

The debate over the continuation of federal funding for scientific research started immediately after the war. The main issues were whether a single central agency should be set up to shape and coordinate scientific research, or whether research funding should be handled through existing departments of the federal government. Another issue was on what basis research contracts should be allocated. The result of the debate was a trade-off: the creation of a new agency, the National Science Foundation (NSF), working in parallel with the traditional agency structure and thus politically accountable to elected officials, while the science establishment and the university community won a commitment to peer-reviewed merit competition for basic science research funding.

The debate took five years: the National Science Foundation was finally established in 1950, but with much smaller funding than originally envisioned by the scientific community. In its first year of funding (1951), the NSF was allocated only \$150,000, and its funding did not exceed \$10 million until 1955. (Source: NSF) The NSF thus became much less dominant as a source of federal funding for academic research than the academic community had originally expected. Meanwhile, the total federal government R&D spending continued to increase and soon exceeded \$1.5 billion annually with \$1.1 billion allocated to the Department of Defense alone. Also, at this time several other agencies emerged. The navy was eager to crack the wartime monopoly of the army and Army Air Corps on developing the atomic bomb; this led to the establishment of the Office of Naval Research in 1946. At the same time, scientists who opposed military control of atomic technology won support for the creation of the Atomic

Energy Commission (AEC). “Like the wartime OSRD, the AEC undertook much of its research via contractual agreements with universities and industry, and it used the contract model to shift from government to university management most of the Manhattan Project's secret government-owned laboratories, including those at Los Alamos, Lawrence, Argonne, Ames, and Brookhaven, and parts of Oak Ridge” (Graham & Diamond, 1997, p.31).

In biomedical research, the demise of the OSRD left a vacuum that was filled by the National Institute of Health (NIH), the research branch of the Public Health Service.⁹

The NIH, which had operated its own in-house or intramural research laboratories since 1930, seized the moment of opportunity in 1945. Taking over fifty wartime research grant projects from the expiring OSRD, the NIH became the chief supporter of extramural research in the nation's expanding network of medical schools. Congress... encouraged the NIH initiative and between 1945 and 1950 expanded its budget from \$3 million to \$52 million.

By 1950 the pluralistic nature of the federal research system was well established, and the new NSF, despite its distinctive primary research mission, was disadvantaged by its tardy entry. The NSF's research funds would modestly enlarge the federal aid pot, but the foundation would not significantly reshape or coordinate national science policy. During the 1950s, federal mission agencies expanded their programs of R&D support under the broad rubric of "mission-related basic research." Under this umbrella, agencies stretched their traditionally applied R&D programs to include basic research, thereby offering universities a growing cafeteria of funding opportunities. (Graham & Diamond, 1997, p. 31)

By 1954, federal agencies still accounted for as much as 69 percent of the funding for the now vastly expanded total university research budgets, while the universities' own funds contributed only 8.5 percent. Meanwhile, the share of private foundations was reduced to only 11 percent and that of industry to 9 percent - both shares sharply reduced from the peaks they had reached in the interwar years. (*ibid.*, p. 32)

⁹ The NIH became plural - the National Institutes of Health – in 1948 when Congress added a separate heart institute to the cancer institute it had created in 1937.

Thus, in conjunction with World War II, a comprehensive array of new federal support programs provided both vastly increased research funding opportunities and considerable competitive pressure. As a result, federal science policy was shaped not by a new ministry of higher education or federal science agency but rather by a whole set of new agencies and programs in already established departments of the federal government. This led to overlapping and often duplicative sponsored research programs which on the one hand invited individual researchers to shop for funding and on the other allowed a broad, experimental research agenda. (*ibid.*, p. 26)

However, the new, federally subsidized research economy of the postwar years by no means provided a blank check to subsidize the research agenda of university scientists and scholars. It is important to note that federal R&D expenditures were allocated primarily to development, not to research. In the early 1950s only 6-7 % of federal R&D expenditures were for basic R&D (and less than 2 % of the R&D funding by the Department of Defense, DoD). Further, most of the federal money (over 80 percent) was spent either by intramural federal agencies or by industry, particularly defense contractors, not universities. In fact, during the 1950s roughly 75 percent of all federal R&D funding was provided by the DoD. In addition, most federal research funds were provided to support applied, programmatic research, not basic, "pure," or "disinterested" research. Even the federally funded basic research program was dominated by "big science" projects with military applications. (*ibid.*, p. 32) For example, in 1956 the budget for basic science research was \$78 million at the Department of Defense and \$45 million at the AEC, while at the NIH, the major supporter of "little science" projects in fundamental research, the basic research budget was only \$26 million and that of the NSF

\$15 million. Even by 1960, after a whole decade of rapid funding growth, the NSF still provided only 12 percent of federal R&D funding for basic research. (Source: NSF)

It is noteworthy that while most research funding went to industry, not universities, and was provided by the Department of Defense and other defense-related agencies, the military was also the largest provider of research funding to universities. In 1963, the DoD provided 26.4 % federal R&D funding to academic institutions, the AEC 8.4%, and NASA 5.8%. Thus, together these three agencies were responsible for 40.6 %, while the NIH provided 36.6%, USDA 5.0%, and other federal sources (including the NSF) 4.9%. Altogether, the federal government funded 70 percent of the total funds for academic research. Under the terms of the federal research contracts, the funding agencies owned the intellectual property rights to the research results and were responsible for their application and implementation in their own domains – a form of commercialization. Philanthropic organizations, state governments, and internal sources provided the remaining 30 percent of funding. (Graham & Diamond, 1997, pp. 34-35)

The Sputnik crisis provided the leaders of academic science with a window of opportunity during the Eisenhower and Kennedy presidencies, and the [President's Science Advisory Committee] enjoyed a half-decade of high visibility and effective policy advocacy. During these years, 1958-63, federal policy makers made two historic decisions. First, the federal government assumed primary responsibility for supporting basic research in the United States. Second, the research enterprise was to be carried out primarily by the nation's universities as an integral component of graduate education. The Seaborg Report explained the rationale for a partnership between the national government and the universities based on the symbiosis of graduate education and research: "Whether the quantity and quality of basic research and graduate education in the United States will be adequate depends primarily upon the government of the United States. From this responsibility the Federal Government has no escape." "Either it will find the policies – and the resources which permit our universities to flourish and their duties to be adequately discharged, ... or no one will." (Graham & Diamond, 1997, p. 33-34)

As a result of the post-Sputnik surge in research expenditures, federal funding for

basic science raised the “pure science” component of university research expenditures on American campuses from 52 percent in 1953 to 76 percent in 1963. The total federal budget for R&D grew by 250 percent in constant dollars between 1953 and 1963, and federal funding of university research grew by 455 percent. (*ibid.*, p. 34)

The fact that the bulk of the R&D continued to involve applied research or development work and was carried out either intramurally or by large defense contractors meant that the research was commercialized rapidly. This was harvest time for the companies that had invested heavily during the war and immediately after. As a result, the growth was largely concentrated in large existing companies, not startups. The total number of concerns in business was about 2.1 million in 1946 (about the same as in 1930) and rose to 2.7 million by 1949 and then stayed at that level until the end of the 1950s. Few new companies were formed; the number of new business incorporations was around 100,000 per year in the latter half of the 1940s, rose gradually in the 1950s and 1960s but did not really take off until the late 1970s. Nonagricultural self-employment stayed constant from the late 1940s until the mid-1960s, even though the labor force grew (i.e., the self-employment rate declined). There were few Initial Public Offerings (IPOs), and those that did occur were quite modest in size (in terms of proceeds per IPO) and often involved companies that had been started many years earlier (Ibbotson *et al.*, 2001). The number of organizations per person declined continuously from 1948 to about 1970 and then leveled off. See Figure 3.

Military considerations clearly dominated the national research agenda during the first two decades after the war. There were close links between basic science and commercial application; even though the ‘big science’ projects were targeted primarily

for the military, the postwar work was mainly applied, and much of it resulted in products that found increasing civilian use (and largely via existing companies, not start-ups): computers, jet engines, radar, and penicillin are prime examples. Huge investments had been made during the war to produce tanks, trucks, jeeps, airplanes, warships, and ammunition. These investments and technologies as well as the knowledge about how to organize and manage mass production were converted to civilian use. The effects lingered for several decades as mass production thinking became dominant in U.S. manufacturing (Carlsson, 1984). Meanwhile, the trade liberalization and economic integration that began at the end of World War II (manifested in the establishment of the United Nations, The World Bank, IMF, GATT, OECD, etc.) provided opportunities for the industrial giants to expand as they converted from military to civilian production.

During this period the knowledge filter was thin and easily penetrated. While knowledge creation in traditional fields went on as before, with little desire to commercialize the results, there was a huge increase in knowledge creation in science and engineering. Most of the new knowledge was applied and quickly converted into new products, mostly military in the beginning but increasingly civilian. As owners of the intellectual property, the federal agencies were responsible for commercialization, and incumbent firms were the main vehicles to do that.

1965-1980: A Period of Transition

After the first two decades following World War II the economic landscape shifted. Concerns were being raised about the rise of the military-industrial complex against whose consequences President Eisenhower had warned. After the onset of the

Cold War, the Korean War, and the Sputnik challenge, military expenditures began to decline, at least in relative terms. Although the Department of Defense was still the major source of R&D funding, federal R&D expenditures grew more slowly than GDP. As a result, R&D as a share of GDP fell from 2.9 % in 1964 to 2.1 % in 1979. See Figure 2. Meanwhile, non-federal (mostly industrial) R&D spending stayed constant in relation to GDP during the 1960s and 1970s and began to increase in the late 1970s, surpassing federal R&D expenditures in 1978. By the end of the 1970s the federal government was no longer the primary source of research funding.

While the share of military R&D declined, the share of basic R&D spending stayed constant. As a result, there was a shift toward more basic R&D in the national research portfolio. R&D funding for basic research as a share of total federal R&D funding increased from 7 % in 1959 to 13 % by 1972. This share then increased steadily from the end of the 1970s to reach 25 % in the early 2000s.

In addition to this shift from applied to basic R&D there was also a change in the locus of the R&D effort. The fact that the research funding was still highly concentrated to only the top universities, most of them private, became a political issue:

Only 492 institutions of higher education (of a total of 2,139) were awarded federal R&D funds in fiscal 1963. Of the \$830 million total, the top hundred recipients won 90 percent. By 1963 the flood of R&D funds to university campuses, most of it awarded competitively by peer review panels at the NIH, the NSF and other agencies, was distributed to a growing number of institutions. But it remained concentrated in the hands of a familiar few. (Graham & Diamond, 1997, p. 34)

Predictably, this allocation of resources was defended by the representatives of the top universities. Former Harvard president Conant wrote: “In the advance of science and its application to many practical problems, there is no substitute for first-class men. Ten

second-rate scientists or engineers cannot do the work of one who is in the first rank.”

(*ibid.*, p. 36) Nevertheless, this concentration of taxpayer support to a few elite

universities was challenged in the 1960s.

As egalitarian, populist pressures grew in the 1960s, the Kennedy and Johnson administrations responded by retaining the core formula of agency funding through peer-review competition, but added new policies and programs in three areas. First, agencies were directed to widen the geographic distribution of federal research support, emphasizing physical facilities and attempting to double the number of strong research universities. Second, federal research support was extended to include the social sciences, the humanities, and the visual and performing arts. Third, federal support was significantly expanded, extending beyond the roughly one hundred doctorate-granting universities, to provide funding for construction and nonscientific programs, including student financial aid, to more than three thousand institutions. These included community colleges, private liberal arts colleges, state colleges and regional universities, historically black institutions, and vocational and proprietary schools. Thus, in the Great Society agenda, federal science policy expanded and blurred into higher education and social policy. (*ibid.*, p. 27)

As a result of these changes, the national R&D effort became less focused and more dispersed. The rate of new knowledge creation declined, as indicated by the falling share of R&D in GDP. Also, while the share of basic R&D increased sharply (as that of applied R&D declined), the potential of commercialization diminished as the beneficial economic effects would occur only with greater delay. In addition, a significant share of the basic R&D funding went to educational purposes and building of research infrastructure rather than into ‘pure’ research. As research projects were increasingly built around clusters of large-scale equipment, often requiring special facilities and support staff, they became enmeshed in the difficult process of institutional-level priority-setting, since accepting these project assignments often meant making major capital investments. In this sense, the knowledge filter was clogging up at the same time as new knowledge creation was slowing down. The institutional barriers to commercialization that had always existed were still there; the research effort was less focused; and the

federal agencies were becoming less successful in converting research into economic activity.

At the same time, the industrial landscape was also shifting. Antitrust regulation and its enforcement prevented both horizontal and vertical integration, leaving conglomeration as the only option beyond organic growth. As time went on and companies engaged in conglomeration in order to expand, they started to lose touch with their knowledge base (their absorptive capacity was reduced). In this sense, too, the knowledge filter started to clog up. The civilian spin-offs from military products began to decline. Many large firms found it difficult to grow during this period. The share of small firms in manufacturing began to grow, reversing the trend toward larger firm size during the previous 100 years (Carlsson, 1992). Some indicators of entrepreneurial activity began to change. The number of self-employed persons outside of agriculture plummeted in 1966-68 and then recovered slowly, reaching its previous level only in 1978, rising slowly until about 1990 and remaining roughly constant since then. The number of organizations per 1000 people, which had declined steadily since 1948, leveled off around 1970. New business incorporations started to increase in the late 1960s. The number of IPOs was low in the 1960s but rose temporarily to a much higher level in the early 1970s, only to fall to extreme lows in the latter half of the 1970s.¹⁰ These developments are illustrated in Figure 3. With the arrival of the microprocessor and recombinant DNA, as well as higher oil prices, in the early 1970s, additional forces were set in motion. The industrial giants were no longer able to absorb the new technologies; new mechanisms and new institutions were necessary.

¹⁰ The rise in IPOs was probably due mainly to institutional reforms that lowered taxes on capital gains and allowed institutional investors such as pension funds to invest in venture capital firms. This made it possible for old but privately held firms to go public.

1980-2006: The Knowledge Filter Unclogged

It was against this background of diminished dynamism in the economy (but with a few signs of a new era of entrepreneurial activity emerging) that a number of institutional reforms were made in the early 1980s. One of these reforms was the Bayh-Dole Act, passed by the U.S. Congress in 1980. It was apparent that the federal research funding was yielding meager economic results. The purpose of the legislation was to help unclog the knowledge filter by transferring the intellectual property rights to research funded by the federal government from the funding agencies to the universities in which the research was carried out. This provided incentives for the universities to commercialize the results of their research. The economic impact was observable in the subsequent period as the number of licenses issued by universities and the number of startups began to increase.¹¹

About this time, reforms were also made that permitted pension funds to invest in venture capital partnerships, giving rise to institutionalized venture capital. This helped unleash the growth of a new form of entrepreneurial finance. Between 1946 and 1977 the creation of new venture funds amounted to less than a few hundred million dollars annually. Starting in the late 1970s, and culminating in the late 1990s, fundraising in the venture capital industry increased sharply (Kortum and Lerner, 2000). While most of this money went to IPOs and new business startups, some of it was used to fund industrial innovation. It is estimated that venture capital accounted for 8 % of industrial innovations during 1983-1992 and 14 % by 1998. (Kortum & Lerner, 2000, p. 691)

¹¹ As important as Bayh-Dole was, it was essentially an attempt to “reverse engineer” the technology transfer process that had worked so effectively in prior years at a few very special institutions such as MIT and CalTech. In the face of the incentives offered by Bayh-Dole, a wide range of universities adapted to a new landscape and began promoting technology transfer, but the vast majority of them never developed the kind of permissive, entrepreneurial culture that marked the early models.

Another step in unclogging the knowledge filter was the establishment in 1982 of the Small Business Innovation Research (SBIR) program. The program requires a wide range of federal agencies with extramural research budgets to set aside a portion (2.5 %) of their research funding for small businesses (<500 employees). Over \$10 billion has been awarded by the SBIR program to various small businesses since 1982. Also, deregulation, especially in telecommunications and transportation, gave rise to new entrepreneurial opportunities. Further, the 1980s and 1990s witnessed a fundamental re-organization of U.S. business. In the biggest mergers and acquisition wave in U.S. history, most conglomerates were broken up and business units were re-bundled. Companies became more focused on their core competencies. One result of this restructuring was a re-organization of corporate R&D. Many central R&D labs were closed, and others were reduced in size while also focusing more narrowly on applied research with a clear commercial objective; basic research (with no foreseeable commercial application) was reduced in industrial firms and shifted instead to the universities which have picked up the role as major performers of basic R&D.

Meanwhile, R&D spending as a share of GDP rose again, from 2.1 % in 1979 to 2.7 % in 1984 and has since remained at about that level. See Figure 2 above. The increase was due to a modest increase in federal R&D spending and a sustained increase in nonfederal (primarily industrial) R&D that continued until 2000. After 1987 there has been a decline in federal R&D spending as a percentage of GDP, but the continued growth in nonfederal R&D has kept R&D/GDP constant. Meanwhile, federal R&D funding has shifted toward basic R&D which now represents about 25 % of total R&D funding. Applied and development R&D is now funded overwhelmingly by industrial

firms. A larger share than ever before of the creation of applied knowledge is now both funded and performed by the entities closest to commercialization, the industrial firms themselves. This makes for a thin knowledge filter.

The structure of R&D at the national level has changed also in another way as the life sciences have absorbed an increasing share of R&D expenditures. Particularly in the biotech arena, this has meant a shift of basic research toward academic institutions. The new discoveries have typically been made in universities, as the absorptive capacity of existing companies (mostly pharmaceutical firms based on chemistry and chemical engineering know-how) was quite limited in the new technology arena. The time lag between scientific discovery and commercial application has turned out to be much longer than in the electronics field – clearly, part of this is due to the approval process requirements of the U.S. Food and Drug Administration and other key agencies. And the transfer mechanism has turned out to be not the large pharmaceutical firms but rather new firms dedicated to biotechnology research who can translate the basic research into commercial knowledge. But in most cases (Genentech being a notable exception), the commercialization in the form of production, marketing, and distribution has been carried out by established pharmaceutical firms, creating a new division of labor and symbiosis between these two groups of firms.

New entrepreneurial opportunities have arisen through scientific and technical advances and changes in government policies. Changes have occurred in the entrepreneurial infrastructure, e.g., via greater availability of professional services and stronger intellectual property protection. There have also been shifts in values, preferences and attitudes toward entrepreneurship. For example, a study of MIT alumni

shows that the entrepreneurial activity of MIT alumni increased steadily (as measured by first firm founding per 1000 alumni) during the 1950s, 60s, and 70s and has then stayed at a high level (Hsu, Roberts and Eesley, 2006). The impact of universities on industry occurs not only directly through transfer of technical knowledge but also through the entrepreneurial activities of alumni.

As a result of all these institutional and structural changes, the last two decades have witnessed a period of a new kind of dynamism in the form of growth of new industries and renewal of old ones as the digital economy has penetrated into all parts of society. Whereas in the early postwar period innovation tended to be carried out by large firms in capital-intensive, concentrated industries characterized by highly differentiated goods, the last two decades have been characterized by a different technological regime in which innovation is carried out primarily by small firms in industries that are highly innovative, skilled-labor intensive and have a large share of large firms (Winter, 1984; Acs & Audretsch, 1987; Plummer & Acs, 2005). Jovanovic has shown that the performance of small companies vs. large ones (as measured by the price of small capitalization stocks relative to the S&P 500) was about equal from the end of World War II to the late 1960s and then rose dramatically to a 4:1 ratio by the mid-1980s (Jovanovic, 2001, p. 54). He attributes this rise in the relative performance of small firms to the arrival of the microprocessor. He also notes that among the twenty largest U.S. companies by market capitalization in 1999, ten were incorporated in or after 1967.

There are two main reasons why small firms have become more important in recent decades. One is that small firms simply do certain things (such as certain types of innovation) better than large firms. As a result, through division of labor between small

and large firms, the efficiency of the economy is increased. The other reason is that small firms provide the entrepreneurship and variety required for macroeconomic growth and stability (Carlsson, 1999).

Some of the results of the increased dynamism of the U.S. economy in the last two decades are captured in Figure 3.¹² As knowledge creation (as measured by the R&D/GDP ratio) picked up after 1980, and as various institutional reforms were made, there was a dramatic increase in entrepreneurial activity in the United States. The number and gross proceeds of IPOs rose markedly in the early 1980s. New business incorporations started to rise in the late 1970s and continued to rise to the mid-1990s. Non-agricultural self-employment also rose from the late 1970s to the mid-1990s.¹³ Nonfarm business tax returns have been on a steady rise since 1980 (the earliest year for which data are available). The number of organizations per person made a dramatic jump in 1984 and has continued to rise rapidly.

Thus, the early 1980s appears to have marked a turning point in U.S. economic growth, representing a transition to a new technological regime in which new business formation plays an increasing role in converting new knowledge into economic growth, thereby reducing the knowledge filter.

¹² This is consistent with Phelps's view that "dynamism requires that innovation be ample, aimed in good directions and finding managers and consumers open to novelty" (Phelps, 2006).

¹³ Blau attributes the rise in self-employment to technological change in the form of personal computers, "government safety and health regulations that favor the self-employed over businesses with employees, and demand-induced changes in industrial structure favoring industries in which self-employment is common." (Blau, 1987, p. 464)

SUMMARY AND CONCLUSIONS

This paper has examined the sources of knowledge creation in the United States over the last century and a half and the mechanisms through which economic knowledge has been converted into economic activity. Prior to the establishment of land-grant universities after the Civil War, there was not much academic research that resulted directly in economic growth. But the rapid growth of universities and enrollment in higher education in the latter half of the 19th century created a much larger college-educated labor force in the United States than in Europe. The resulting increased capacity to absorb new technology was strengthened by the practical orientation of U.S. higher education. Economically useful knowledge creation in the late 19th century was largely informal and took place in industrial laboratories whose main tasks were testing, measuring, and standardizing industrial products and processes.

As science-based industries such as the chemical, electrical machinery, and telecommunications industries began to grow in the late 19th century, new scientific knowledge was needed. The creation of such knowledge required research facilities utilizing specialized equipment and skills on a scale beyond the capabilities of the universities. Industrial firms such as Du Pont and General Electric therefore built their own corporate R&D labs. It is in such laboratories, as well as in federal government laboratories, that most economically useful R&D, including basic research, was conducted until after World War II. The vast bulk of industrial R&D has always been commercially oriented, resulting in new and improved products and processes. This is true even today.

Before World War II, basic research in the universities was quite small. Total external funding of academic research did not exceed \$50 million annually prior to World War II, and all of this came from foundations and a few industrial companies. The federal government played no role in funding academic research. But World War II led to fundamental changes in the knowledge creation system. The military effort led to a massive increase in R&D spending. Most of the funding came from the Department of Defense and was conducted largely in government labs and by defense contractors. But the war-related research was organized in such a way that it also involved universities. For the first time, and quite suddenly, the federal government became the major source of funding for academic research which now included “big science” projects (systematic, programmatic research) on a scale never seen before. Basic research started to shift toward the universities. As the war ended, the G.I. bill generated a large increase in college enrollment. The war-related products (such as computers, jet engines, and radar) that resulted from the R&D were commercialized almost immediately through the military and soon after the war were converted into civilian products. The commercialization took place through incumbent firms. There were few new firms created; entrepreneurial activity declined or stagnated between 1950 and 1965.

The federal funding of defense-related R&D continued to grow until total R&D expenditures reached a peak in the mid-1960s. The total R&D spending then fell as the federal expenditures declined. Also, the federal funding of academic research now became less focused, dispersed to a much larger number of institutions of higher education, and used for building research infrastructure. As a result, much less of the knowledge created was economically useful; the knowledge filter was clogging up. The

civilian spin-offs from military products began to decline, and the economic growth rate fell.

1980 represents something of a turning point. A number of institutional reforms (including the Bayh-Dole Act and changes in tax laws and regulation of financial institutions) mark a transition to a new technological regime in which new business formation plays an increasing role in converting new knowledge into economic growth. The breakthrough in DNA research and the microprocessor revolution also played a role. Entrepreneurial activity (as measured by non-farm business tax returns, new business incorporations, the number of organizations per capita, the number of IPO offerings, and non-agricultural self-employment) began to pick up as the dynamism of the economy increased.

The 'big picture' that emerges is one which shows the economy becoming increasingly dependent on economically useful knowledge and on the effectiveness with which that knowledge is converted into economic activity. In the late 19th century the knowledge creation was linked to a rise in the share of college-educated people in the population and codification and standardization of economically useful knowledge in industrial labs. At the turn of the 19th century, economic growth was driven primarily by science and engineering-based industries such as chemicals, electrical equipment, and telecommunications. The leading companies in these industries built their own corporate R&D labs. These, as well as several federal laboratories, were the main producers of economically useful knowledge, and they were quick to reap the economic benefits.

World War II led to a massive scaling up of R&D in the United States. While most of the funding went to federal and corporate laboratories, the federal government

now also began to fund academic research. At first the defense-related R&D was immediately converted into economic activity via incumbent firms producing such products as jet engines, radar, and computers. In the mid-1960s, the total R&D expenditures started falling in relation to GDP, and the economic impact of the war-related products was diminishing. The decline in R&D spending was reversed in the early 1980s, carried largely by biotechnology and the microprocessor.

The main conclusions of this paper are (1) that in order to explain economic growth it is necessary to distinguish between general knowledge and economically useful knowledge; (2) that the effectiveness with which such knowledge is converted into economic activity varies over time and depends on institutions; and (3) that the mechanism converting economically useful knowledge into economic growth also varies over time. Until the late 1970s, incumbent firms were the main vehicles. Subsequently, new ventures have been the main mechanism.

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Figure 1 The Knowledge Filter in the Knowledge Creation System

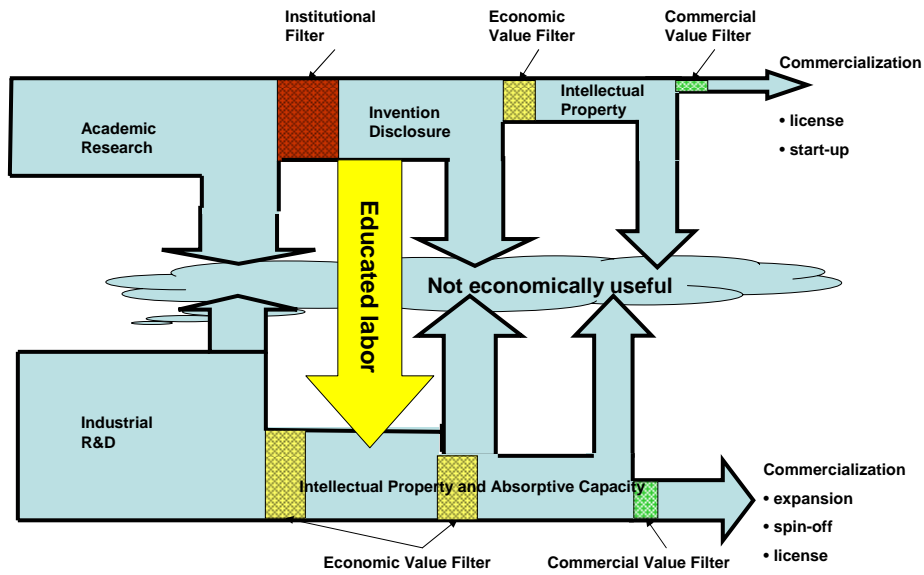
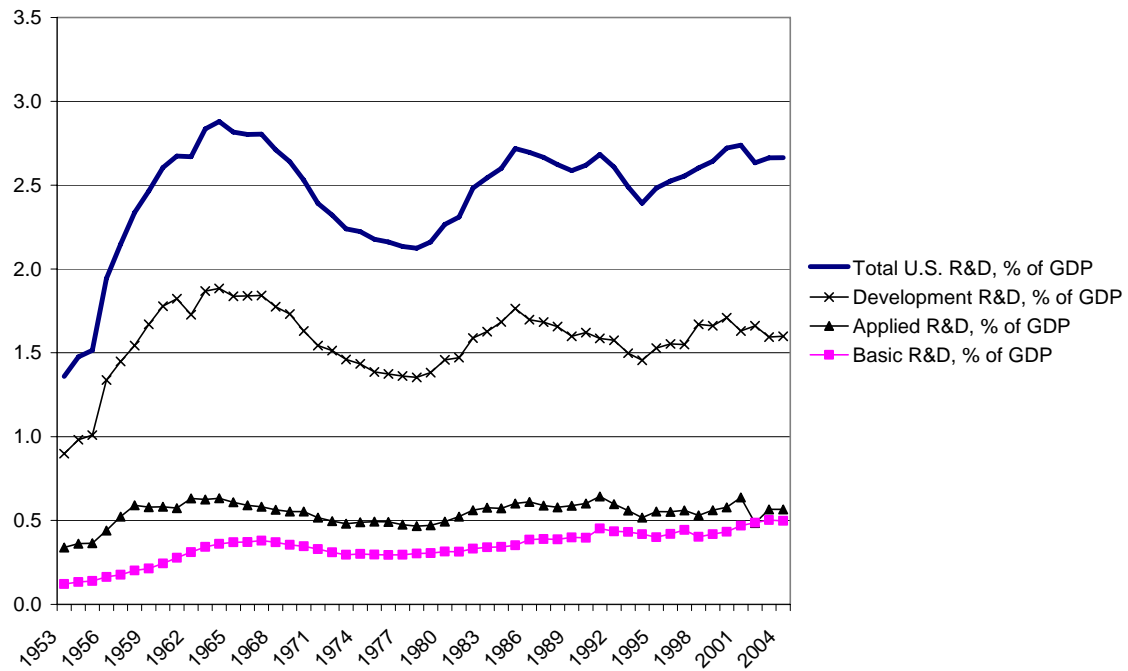
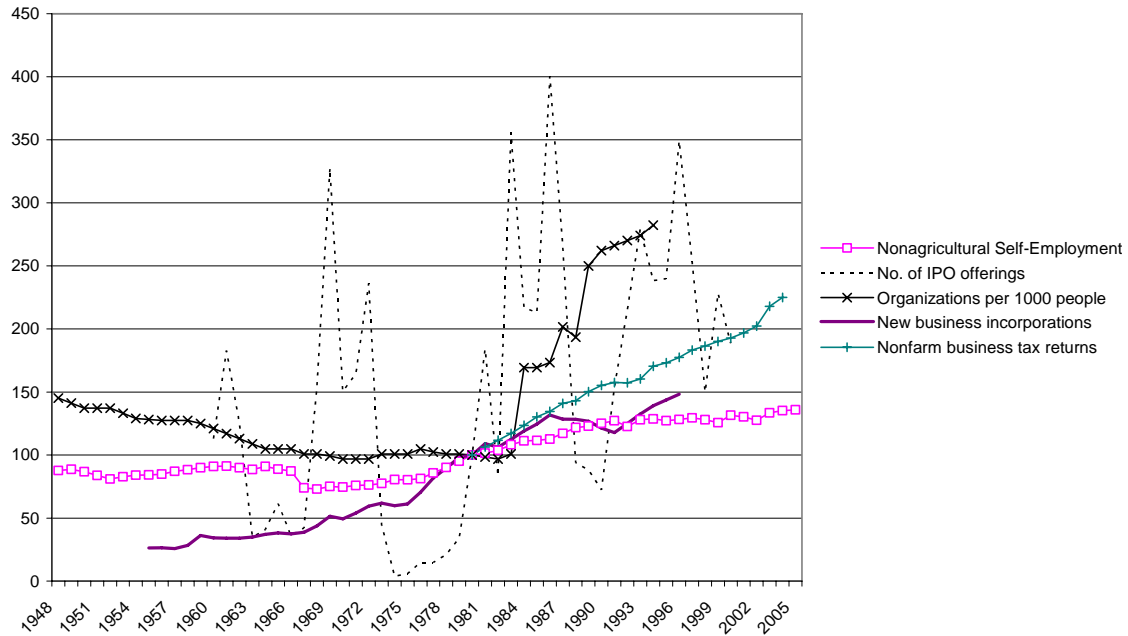


Figure 2. U.S. R&D as % of GDP, 1953-2004



Sources: NSF, <http://www.nsf.gov/statistics/>. U.S. Bureau of the Census, *Statistical Abstract of the United States*, various issues.

Figure 3. Indicators of Entrepreneurial Activity, 1948-2005
Index, 1980=100



Sources: Number of IPOs: Ibbotson et al. (2001); Ritter (2006). New Business Incorporations, Nonfarm business tax returns, and Nonagricultural Self-Employment: *Statistical Abstract of the United States*, various issues. Organizations per 1000 people: Gartner and Shane (1995), p. 295.