Nanotechnology and the U.S. national innovation system: Continuity and Change[1]

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Introduction

The development of nanotechnology has been spawned a large body of research on the economic and societal implications of this new technology. Much of this literature emphasizes the ways in which nanotechnology research represents a "New Wave" of public policy and inter-institutional relationships in the U.S. national innovation system, a concept that I define in greater detail below. At least two closely linked elements of novelty are cited by proponents of the "new wave" characterization (for one representative account, see Johnson, 2004): (1) Federal R&D funds are focused on economic objectives, rather than supporting fundamental research aimed at advancing knowledge; and (2) the policies adopted U.S. universities in nanotechnology research represent a new approach that has been labeled "post-academic research," emphasizing the commercialization of discoveries through licensing of academic patents.

In fact, however, these characterizations of nanotechnology research, while accurate, highlight elements that are not novel. Although the policies and institutions within which nanotechnology research now is carried out have changed in some respects, there are also important continuities in U.S. public policy and in the ways in which U.S. universities have supported innovation in nanotechnology. It seems important to focus on the elements of genuine novelty, rather than emphasizing those that are of secondary importance, and I undertake such an analysis in this brief overview.

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The U.S. “national innovation system”

The “national system of innovation” (NSI) framework for analyzing innovative performance and policy has been an influential area of scholarship for more than 20 years, since the first articulation of the concept in Freeman (1987; see also Lundvall, 1992 and Nelson, 1993). “National” innovation systems typically include the institutions, policies, actors, and processes that affect the creation of knowledge, the innovation processes that translate research into applications (either for commercial sale or deployment in such “nonmarket” contexts as national defense), and the processes that influence the adoption of innovations. As such, the U.S. national innovation system includes not just the institutions performing R&D and the level and sources of funding for such R&D, but policies—such as antitrust policy, intellectual property rights, and regulatory policy—that affect technology development, the training of scientists and engineers, and technology adoption. In addition, institutional elements, such as national systems of higher education and systems for corporate finance and governance, are important components of national innovation systems. The structure of a nation’s innovation system is the result of complex historical processes of institutional development, in addition to public policy. Moreover, the performance of these systems depends in part on the actions and decisions of private enterprises that can reinforce or offset the effects of public policies.

In the U.S. context, the applicability of all three of the terms included in the “national innovation system” concept is subject to some debate. First, the U.S. “innovation system” clearly spans national boundaries, as cross-border flows of people, technology, and capital play a central role in the evolution of the U.S. system and mediate the effects of innovation in the United States on other nations throughout the global economy. Indeed, a recurring debate in the literature on “national innovation systems” concerns the extent (if any) of convergence among the national innovation systems of the industrial economies, in part as a result of cross-border interactions of the sort noted above.

A second conundrum within the U.S. “national innovation system” concerns the extent to which innovation alone is the central phenomenon of interest. As I pointed out earlier, it is almost meaningless to confine the definition of a national innovation system to innovation alone—research, invention (in the sense defined by Schumpeter, 1932), and technology adoption are essential components of the broad concept. More than innovation alone must be incorporated into any workable definition of a "national innovation system," although innovation per se clearly is central to the concept.

Finally, the U.S. national innovation system, notably the public policies in the areas of R&D funding, antitrust, and intellectual property (to name only a few of the most obvious such policies), can hardly be described as a "system," in the sense of a coherent web of policies whose formulation and implementation result from a coordinated process. Instead, observers have long emphasized the extent to which U.S. innovation policies have emerged from the interaction of policies developed independently of one another, spanning a diverse array of fields (See Mowery and Rosenberg, 1993, 1999).

For all of these reasons, it is important to keep in mind that the "national innovation system" concept should not be pushed too far in the context of the United States. Nevertheless, the innovation system concept remains relevant and useful as a heuristic device for highlighting elements of continuity and change in nanotechnology R&D and technology policy within the United States.

Nanotechnology: A "new wave" within the U.S. national innovation system?

The social science literature on nanotechnology has highlighted several elements of innovation-related processes and policies that represent significant departures from the historical evolution of the U.S. national innovation system. According to its proponents, this "new wave" is most apparent in the characteristics of federal-government funding of nanotechnology R&D and in the inter-institutional relationships that (it is claimed) characterize nanotechnology R&D and innovation.

In this view, the major U.S. federal government interagency program for support of R&D in nanotechnology, the "National Nanotechnology Initiative" (NNI), represents a significant break with the philosophy underpinning large-scale federal support of R&D in industry and especially, academia since 1945. For most of this period, supporters of the "new wave" argument contend, federal funding of science emphasized basic research, sought fundamental advances in knowledge, and granted great autonomy to academic scientists in establishing their research priorities. The architect of this approach to R&D funding, of course, was Vannevar Bush, author of the famous 1945 report, *Science—The Endless Frontier*. Bush's argument, elaborated in economic terms by leading postwar economists such as Nelson (1958) and Arrow (1962), justified public funding of such research as necessary because of the inability of private industry to capture the economic returns from these investments. Government support of fundamental research thus addressed a key "market failure" in industrial economies, and was essential to expand the knowledge base on which industrial innovation relied.[2]

The NNI has transformed the terms of this "social contract," according to some scholars. Johnson (2004) and McCray (2005) argue that the NNI's support of research in universities in fact is an example of "post-academic research":

> This regime is characterized by an emphasis on the utility of science and the enlistment of academic research as a 'wealth-creating technoscientific motor for the whole economy,' views clearly expressed in the documents and testimony supporting the NNI… While the end of the Cold War is certainly relevant, the changing nature of research funded by the federal government and conducted at universities is even more significant. Since the passage of the Bayh–Dole act in 1980, the 'triple helix' of relations between the academy, industry, and government has been significantly altered and strengthened…The borders between science and technology, as the NNI implementation plan shows, have blurred while the commercialization of academic science has become a key driver for its funding. (McCray, 2005, p. 192).[3]

In this view, public funding of academic R&D in nanotechnology now is motivated by an interest in economic outcomes, rather than a commitment to advancing fundamental knowledge. Partly because of

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[2] Martin (2003, p. 9) highlights "…several essential characteristics of the Bush social contract. First, it implied a high level of autonomy for science. Second, decisions on which areas of science should be funded should be left to scientists. It therefore brought about the institutionalization of the peer-review system to allocate resources, a system used before the Second World War by private foundations that supported research. Third, it was premised on the belief that basic research was best done in universities (rather than government or company laboratories)."

[3] "In the 1950s and 60s, science and technology policy was guided by the 'pipeline' model of the relationship of science to technology championed by Vannevar Bush…In this scheme, federally funded basic science would provide the new knowledge that underpinned new technological developments. Government spending needed to focus on basic, non-targeted research because this kind of scientific work was both fundamental and less attractive to the private sector…As economic circumstances worsened after 1973, policy makers wanted to demand more economic bang for their research buck. American scientific research had to be part of the solution: American scientific superiority needed to translate into economic performance. But to do so, the role of the federal government had to change, and these changes took over a decade to put into place…

…the focus of much federal science and technology policy in the 1980s was on problems in the movement and translation of knowledge from the lab through development into the market."(Johnson, 2004, p. 219).

this emphasis on innovation-related results, the NNI also emphasizes university-industry collaboration and "technology transfer," characteristics of research organization and policy that other scholars now refer to as "Mode 2" (Gibbons et al., 1994) while others highlight the emergence of a "Triple Helix" of inter-institutional collaboration that spans industry, government, and universities (Etzkowitz, 2008).

Although the market failure rationale retains rhetorical influence as a justification for public R&D investments, casual empiricism suggests that its influence over such public investments has long been modest. Most OECD nations' R&D investment budgets are dominated by programs that serve specific government missions, such as defense, agriculture, health, energy, and other activities. The "market failure" rationale underpins less than 50% of public R&D spending in most of these economies. Data from the National Science Foundation (National Science Board, 2006) on "mission-oriented" and "nonmission-oriented" R&D spending for six industrial economies[4] and one middle-income industrializing economy (South Korea) for 2003-2004 show that in none of these nations does "nonmission" R&D account for as much as 50% of central-government R&D spending, and in most of them, "mission-oriented" R&D spending accounts for more than 60% of the public R&D budget. The United States is an outlier, with large R&D programs in defense and health bringing the total "mission-oriented" R&D budget to well over 90% of federal-government R&D spending. Also noteworthy is the relatively small share of central-government R&D spending accounted for by the "Bush-Arrow" form of R&D spending, nonmission-oriented R&D. This class of public R&D investment accounts for nearly 30% of reported central-government R&D spending in France and Germany, but is well below 20% in the United Kingdom and Canada, and barely exceeds 5% in the United States.

The structure of mission-oriented R&D programs differs among federal agencies and missions nearly as much as the structure of such programs differs from that of "Bush-Arrow" R&D programs. A comparison of the mix of basic, applied and development spending in U.S. defense-related and biomedical research (the two leading fields of mission-oriented R&D in the U.S. federal budget) suggests

[4] Germany, Japan, France, the United Kingdom, Canada, and the United States. The "mission-oriented" categories of R&D spending, chosen to make these national data as comparable as possible, are defense, space exploration; energy, agriculture, industrial technology development, and health.

that the distribution among performers and R&D categories of biomedical R&D resembles that of the National Science Foundation's R&D spending more closely than it does the Department of Defense R&D programs. Although these features of publicly funded biomedical R&D are similar to those of the leading "Bush-Arrow" public R&D program in the United States, the rationale for the enormous U.S. investment of public funds in biomedical research has little to do with market failure—after all, biomedical research is characterized by relatively strong intellectual property rights, and industry-financed R&D spending has outstripped public R&D funding since the 1960s.

The large mission-oriented R&D programs supported by public funds in the post-1945 United States have yielded important economic benefits. Much of the innovation underpinning electronics and information technology (IT), ranging from semiconductor components to computer software and the networking technologies that led to the Internet, was supported by Defense Department funds allocated to industrial and academic researchers (See Mowery, 2010a, 2010b). Similarly, the competitive strength of the postwar U.S. pharmaceuticals and medical devices industries, as well as the growth of biotechnology, owe a considerable debt to R&D funded by the federal government through the National Institutes of Health (Mowery et al., 2009).

The governance of many of these large public investments in mission-oriented R&D also bears little resemblance to the idealized portrait of the "[Vannevar] Bush social contract"[5] articulated in Guston and Keniston (1994). Rather than "scientists" controlling the allocation of public R&D funds, allocation decisions in these R&D programs were based on assessments of the research needs of specific agency missions ranging from national defense to agriculture. Indeed, at least one important postwar program of defense-related R&D, the U.S. Defense Advanced Research Projects Agency's (DARPA) initiative to create academic "centers of excellence" in the embryonic field of computer science, peer review played a

[5] Martin (2003, p. 9) highlights "…several essential characteristics of the [Vannevar] Bush social contract. First, it implied a high level of autonomy for science. Second, decisions on which areas of science should be funded should be left to scientists. It therefore brought about the institutionalization of the peer-review system to allocate resources, a system used before the Second World War by private foundations that supported research. Third, it was premised on the belief that basic research was best done in universities (rather than government or company laboratories)."

minimal role (See Langlois and Mowery, 1996). Although Gibbons and co-authors. (Gibbons et al., 1994) have proclaimed the rise of a new type of publicly funded R&D ("Mode 2"), which is multidisciplinary, motivated by societal needs, and accountable to public funding agencies, in fact "Mode 2" appears to resemble the mission-oriented R&D that has dominated most OECD governments' R&D budgets since at least the 1950s. To a surprising extent, scholarly analysis of the "new context" of science and technology policy fails to acknowledge the prominence of mission-oriented R&D programs that have few of the hallmarks of the idealized "Bush social contract."

The emphasis by many scholars examining the NNI and nanotechnology on the "novel aspects" of federal funding, whether they use the labels of "post-academic research," "Mode 2," or the "Triple Helix," thus overlooks the historical dominance of federal R&D spending in the United States by programs that have focused on specific programmatic or policy objectives, have emphasized outcomes supportive of these objectives, and often have limited the autonomy of the academic signatories to the (Vannevar) Bush "social contract." As I argue below, nanotechnology R&D does exhibit some new features, but these are neither unprecedented nor are they specifically tied to the emphasis by government funding agencies on the attainment of specific objectives. It is of course true that economic objectives now are more prominent within the NNI programs than was true of the R&D programs of the National Institutes of Health or the Defense Department, but this difference concerns the nature rather than the existence of programmatic objectives that go beyond knowledge for knowledge's sake.

What *is* new about nanotechnology in the U.S. national innovation system?

A number of the claims for novelty associated with nanotechnology R&D and the U.S. national innovation system thus appear to be overstated. Nonetheless, nanotechnology R&D does contain some new features that pose challenges for the future performance of this system. These novel features include (1) the intensive patenting of nanotechnology discoveries, even those that are well "upstream" from commercial application; (2) the intensive patenting of nanotechnology discoveries by U.S. research universities that seek to "transfer" these research advances to commercial application through licensing; and (3) the emergence of a vertically specialized structure for innovation in nanotechnology at an early stage of the technology's development.

These three novel elements are closely related to one another, and reflect the fact that the development of nanotechnology, unlike IT or biotechnology, has from its inception taken place in an environment of strong patentholder rights, the so-called "pro-patent era" in U.S. intellectual property rights policy that dates back to the early 1980s (See Mowery, 2010c, for further discussion). One of the most important foundations for the "pro-patent era" was the 1982 legislation that established the Court of Appeals for the Federal Circuit, which specialized in patent cases and strengthened the protection granted to patentholders.[6] But even before the establishment of the CAFC, the 1980 U.S. Supreme Court decision in *Diamond v. Chakrabarty* upheld the validity of a broad patent in the new industry of biotechnology, facilitating the patenting and licensing of inventions (many of which originated in U.S. universities) in this sector. Still another important legislative component of this shift in U.S. intellectual rights policy was the Bayh-Dole Act, passed in 1980.[7]

Other important judicial decisions in private patent litigation resulted in damages awards of unprecedented scale (the Kodak-Polaroid case, which resulted in a damages award of one billion dollars and forced Kodak to close its instant camera line of business in 1986) and extended the scope of patentable intellectual property to include "business methods" (the *State Street* case). The U.S. government also pursued stronger international protection for intellectual property rights in the Uruguay Round trade negotiations and in other bilateral venues.

The consequences of the "pro-patent era" for U.S. economic performance have been the subject of a wide-ranging and inconclusive debate since the early 1990s. One consequence on which there is little debate is the surge in patenting during 1980-2005. Between 1967 and 1984, U.S. patent applications

[6] According to Katz and Ordover (1990), the CAFC upheld patent rights in roughly 80% of the cases argued before it, a considerable increase from the pre-1982 rate of 30% for the Federal bench.

[7] The Act was named after its authors and senior sponsors, Senators Birch Bayh of Indiana (not Senator Bayh's son Evan, erroneously identified by Johnson (2004) as one of the Act's authors) and Robert Dole of Kansas.

grew by roughly 0.3% per year; after 1984, the rate of growth increased to nearly 7% per annum (Hall, 2004). The sharp increase is attributable largely to filings from individual, corporate, and institutional inventors residing in the United States, and it is concentrated mainly in computing and electronics (Hall, 2004).[8]

Nanotechnology R&D in the "pro-patent era"

As an emergent technology in the "pro-patent era," nanotechnology R&D has been characterized by extensive patenting, and some observers argue that these patents now cover more fundamental, scientific concepts, rather than primarily covering innovations that are near to commercialization. This characteristic of nanotechnology contrasts with earlier postwar technological innovations, such as semiconductors, computer hardware, computer software, or even biotechnology at its inception, all of which faced an intellectual property-rights policy environment that was more hostile to patentholder rights, reflected in both judicial decisions and federal antitrust enforcement actions. In addition, a combination of federal antitrust policy actions in computers and semiconductor components, as well as uncertainty over the patentability of life forms, meant that in most of these previous major technological clusters, intellectual property rights were both weaker and more uncertain in the earliest years of the technologies' development.

As Lemley (2005) has noted, the development of nanotechnology is likely to yield important evidence on the effects of extensive patenting on foundational technological or scientific advances in the early years of development of a technology:

> In most other fields of invention over the past century in what we might think of as "enabling" technologies – computer hardware, software, the Internet, even biotechnology – the basic building blocks of the field were unpatented, either because they were created by government or university scientists with no interest in patents, or through mistake, or because the government compelled licensing of the patents, or because the patents were ultimately invalidated. (2005, p. 7)

[8] Other scholars have suggested that this surge in patent applications, particularly those involving relatively new fields of inventive activity such as computer software, has taxed the review capabilities of the U.S. Patent Office, leading to an increase in low-quality patents (Merges, 1999).

Interestingly, patenting in nanotechnology has been extensive in spite of the lack of evidence on the economic value or legal validity of these patents. Although federal policies and judicial decisions have by and large been friendlier to patentholders since 1980, considerable debate remains over the quality of the patents issued by the U.S. Patent Office in the face of rapid growth in applications. Thus far, few if any of the major nanotechnology patents have been challenged in court, nor have infringement actions been resolved on terms that establish the value of these patents. Considerable uncertainty thus remains as to the ultimate value of the nanotechnology patents being issued in the United States. But this uncertainty has not prevented rapid growth in nanotechnology patenting.

FIGURES 1 – 2 HERE

Figures 1 and 2 depict trends during 1975 – 2005 in the share of patenting by U.S.-based entities accounted for by the "nanotechnology" patent class, 977, which was created by the USPTO in 1975. Since this patent class includes a number of patents that in earlier years would have been classified elsewhere, the growth in the share of "nanotechnology" patents in these Figures is somewhat overstated.[9] Nonetheless, both overall U.S.-assigned patents and patents assigned to U.S. corporations and universities display significant increases in the share of nanotechnology patents, which peak at roughly .4% of overall U.S.-assignee patenting in 2001, .3% of U.S. corporate assignees in 2001, and slightly more than .4% of U.S. university patenting in 2001.

As the Figures indicate, U.S. universities have been especially active in obtaining nanotechnology patents during this period. U.S. universities, which accounted for less than 2% of all U.S. patents during 1975-2002, hold more than 15% of all U.S. patents in nanotechnology. Conversely, U.S. corporations' share of nanotechnology patents is smaller than their share of overall U.S. patents. The rapid growth in nanotechnology patenting thus has been driven in part by U.S. universities, another characteristic of nanotechnology R&D that is both novel and potentially challenging for the U.S. national innovation system.

[9] Since these patents are dated by their application dates, the sharp falloff in "patenting" displayed for the 2003 – 2005 period is spurious, reflecting the fact that a much larger share of the patents applied for during these years have not yet issued.

"Post-academic research" in U.S. universities before and after the Bayh-Dole Act

A central part of the argument made by advocates of the "transformation" in U.S. universities' role within the U.S. national innovation system with the rise of nanotechnology concerns the Bayh-Dole Act of 1980 and the role of university patenting. Although U.S. universities have increased their patenting and licensing activities, with uncertain consequences, since the 1980 Act, this shift in the characteristics of university research in fact represents an extension in a longstanding trend, rather than a transformative event. Nevertheless, the increased role of academic patenting in an embryonic technology such as nanotechnology raises important questions.

Collaboration between university and industrial researchers, combined with the focus of many U.S. university researchers on scientific problems with important industrial or agricultural applications, meant that a number of U.S. universities patented faculty inventions throughout the 20th century. Although a number of U.S. universities had adopted formal patent policies by the 1950s, partly in response to the requirements of the federal research funding agencies that expanded their funding for academic research in the post-1945 period, many of these policies, especially those at medical schools, prohibited patenting of inventions, and university patenting was less widespread than was true of the post-1980 period (Mowery and Sampat, 2001b). Moreover, U.S. universities frequently chose not to manage patenting and licensing themselves (Mowery and Sampat, 2001a).

The decade of the 1970s, as much as or more so than the 1980s, represented a watershed in the growth of U.S. university patenting and licensing. U.S. universities expanded their patenting, especially in biomedical fields, and assumed a more prominent role in managing their patenting and licensing activities, supplanting the Research Corporation (See Mowery and Sampat, 2001a). Agreements between individual government research funding agencies and universities also contributed to the expansion of patenting during the 1970s. Private universities in particular began to expand their patenting and licensing rapidly during this decade. The share of biomedical technologies within U.S. university patents had begun to grow in 1972, well before the passage of the Bayh-Dole Act in 1980 (Figure 4).

Having assumed direct responsibility for management of their patenting and licensing activities, U.S. universities began to chafe against the restrictions on their licensing activities imposed by some federal research funding agencies (notably, the NIH). Lobbying by U.S. research universities in favor of less federal oversight of licensing was one of several factors behind the passage of the Bayh-Dole Act in 1980. The Act is as much an effect as a cause of expanded patenting and licensing by U.S. universities during the post-1960 period.

The Bayh-Dole Patent and Trademark Amendments Act of 1980 provided blanket permission for performers of federally funded research to file for patents on the results of such research and to grant licenses for these patents, including exclusive licenses, to other parties. Although it did not legalize anything that had previously been prohibited (federal agencies had long been permitted to negotiate university-specific "Institutional Patent Agreements" that enabled universities to patent and license the results of federally funded research), the Act facilitated university patenting and licensing in several ways. First, it replaced the web of Institutional Patent Agreements (IPAs) that had been negotiated between individual universities and federal agencies with a uniform federal policy. Second, the Act's provisions expressed Congressional support for the negotiation of exclusive licenses between universities and industrial firms for the results of federally funded research. Third, the Act reduced the power of federal research-funding agencies to oversee the terms on which publicly funded research results were licensed to industrial firms.

How did the Bayh-Dole Act affect patenting by U.S. universities? Since overall patenting in the United States grew during this period, indicators of university patenting need to be normalized by overall trends in patenting or R&D spending. Figures 3-4 present two such indicators that span the period before and after the Act. Figure 3 depicts U.S. research university patenting as a share of domestically assigned U.S. patents during 1963-99. Universities increased their share of patenting from less than 0.3% in 1963 to nearly 4% by 1999, but the rate of growth in this share begins to accelerate before rather than after 1980. Figure 4 plots the ratio of aggregate university patenting at time *t* to aggregate academic R&D

expenditures at time *t-1*, for application years 1963-1993.[10] The Figure reveals an increase in aggregate university "patent propensity" after 1981 (as pointed out by Henderson et al. 1998), but this is the continuation of a trend that dates at least as far back as the early 1970s; there is little evidence of a "structural break" in patent propensity after Bayh-Dole.[11]

FIGURES 3 - 4 HERE

Another issue of interest in academic patenting is the distribution among technology fields of university patents during the pre- and post-Bayh-Dole periods. Nonbiomedical university patents increased by 90% from the 1968-70 period to the 1978-80 period, but biomedical university patents increased by 295%. The growth of biomedical research funding within overall federal academic R&D funding, the dramatic advances in biomedical science that occurred during the 1960s and 1970s, and the strong industrial interest in the results of this biomedical research, all affected the growth of university patenting, and academic biomedical patenting in particular, during this period. But as I noted earlier, this shift toward biomedical academic patenting predates the Bayh-Dole Act.

Evidence cited in Mowery et al. (2004) reveals that gross licensing revenues for Columbia University, Stanford University, and the University of California system during the period after the passage of the Bayh-Dole Act were dominated by a small number of patents. For each of these three universities, the “top 5” patents accounted for more than 65% of gross licensing revenues. These “top 5” patents were mainly biomedical inventions. Universities lacking a major biomedical research program may not produce such “home run” patents and therefore may reap lower gross revenues. The high costs

[10] Data on total academic R&D were obtained from National Science Board (2000), Appendix Table 4-4.

[11] Mowery et al. (2004) argued that the Bayh-Dole Act did not dramatically affect the patenting and licensing activities of universities that had long been active in this area, such as Stanford University and the University of California. Indeed, the biomedical patents and licenses that dominated these institutions’ licensing revenues during the 1980s and 1990s had begun to grow before the passage of the Bayh-Dole Act. Columbia University, an institution with little experience in patenting and licensing before 1980 (and an institution that prohibited the patenting of inventions by medical faculty until 1975), also had filed for its first “blockbuster” patent before the effective date of the Act. Nevertheless, the Act did increase patenting of faculty inventions at both Stanford and the University of California, although many of these patents covered inventions of marginal industrial value and did not yield significant licensing royalties.

of establishing and operating technology licensing offices (costs that include the legal expenses associated with patent prosecution and litigation) also depress net revenues.

Even the University of California system (which consisted of nine campuses during the period covered by these data), one of the leading U.S. university recipients of licensing revenue during the "post-Bayh-Dole" era, reaped surprisingly small net revenues from licensing activities. During fiscal 2001-2004 average annual gross licensing revenues for the UC system were roughly $75 million. The net contribution to UC operating expenses, however, a figure that subtracts the operating expenses of the technology licensing office and payments to the faculty inventor, averaged slightly more than $15 million annually. This amount represents a small fraction (less than 1%) of the annual research budget for the UC system of more than $3 billion. Industry funding of academic research within the UC system in fiscal 2001 (the most recent year for which comprehensive data are available) amounted to $235 million, dwarfing both the average gross and net institutional revenues associated with licensing activities.[12]

The dominance of U.S. university licensing revenues since Bayh-Dole by licenses for biomedical patents reflects the unusual legal strength and economic value of patents in this field. Scholars have long emphasized (See Levin et al., 1988) that the power of patents to prevent imitation and enable the inventor to capture the returns to an invention is greatest for chemical and pharmaceutical inventions. The significantly higher economic value of patents in these fields reflects the fact that they are very difficult to "invent around," as well as the tendency for one or a small number of patents to effectively cover all relevant aspects of a specific invention. As a result, the legal power of biomedical patents to exclude would-be imitators is high.

The legal and economic value of patents in biomedical technologies contrasts with their more limited effectiveness in other fields, notably information technology and electronics, where a given innovation more commonly draws on many different patents, the power of any single one of which to exclude imitators is much more uncertain. The more limited power of patents in these fields is reflected in their modest contributions to university licensing revenues. Surveys of industrial R&D managers also

[12] http://www.ucop.edu/research/publications/pdf/resfund01.pdf, accessed February 20, 2006.

indicate that patents per se play only a minor role as channels of knowledge transfer from academia to industry (Levin et al., 1998; Cohen et al. 2002) in fields other than pharmaceuticals or chemicals. Indeed, U.S. firms in the IT sector have voiced considerable criticism of U.S. university licensing policies since 1980, arguing that these policies are obstructing rather than facilitating research collaboration and technology transfer.

In light of the limited effectiveness of patents for licensing and technology transfer in fields outside of pharmaceuticals, chemicals, and biomedical technologies, the high rates of academic patenting of nanotechnology inventions may not contribute significantly to licensing revenues or to the effectiveness of technology transfer through such licensing transactions. Indeed, Mody's discussion (2006) of the development of probe microscopy technologies, critical enabling innovations for the nanotechnology R&D, emphasizes the informal, interactive character of the collaborations between university and industry researchers that spawned the production of probe electron microscopes for application in university and industrial research.[13] Patent licensing was of little or no significance in facilitating these interactions. Do the broad characteristics of nanotechnology R&D and innovation resemble those described by Mody, or is this interactive, informal pattern of collaboration unique to instrumentation? The recent industrial criticisms of U.S. university licensing policies have received considerable support from some senior industrial managers engaged in nanotechnology R&D (See

[13] Mody also criticizes the characterization of nanotechnology research as "post-academic" in terms similar to those used in this paper: "There was no golden age in which faculty operated independently of commerce, pursuing disinterested research. Knowledge-production in physics, engineering, and chemistry was always aided by academic consulting and the exchanging of personnel and ideas. The oft-criticized commercialism of the "biotech revolution"merely extended long-standing entrepreneurial practices into molecular biology." (2006, p. 80).

Williams, 2002).[14] Academic patenting in nanotechnology R&D thus may create impediments to industry-university collaboration.

Although extensive academic patenting in nanotechnology may not facilitate university-industry technology transfer or research collaboration, the broader effects of patenting embryonic scientific discoveries remain unclear. Specifically, what is known about the effects of patenting on the progress of basic scientific research? Will academic researchers motivated by the prospect of financial returns from patenting and licensing their discoveries, become less willing to share information and research materials? Alternatively, will university intellectual property regulations interfere with the free flow and exchange of information and research materials, either through patenting of inputs to science or through other restrictions on information exchange? Will the "transaction costs" of conducting biomedical research increase, impeding the advance of scientific research?

Previous work on this topic has examined the effects of increased patenting on biomedical researchers' willingness to share information on their work in progress (Blumenthal et al., 1997; Campbell et al., 2002). More recent research has analyzed the effects of patenting of discoveries that are also disclosed in scientific papers on the extent of citation to these papers, and finds that the issue of a patent results in modest but significant declines in citations to the research papers related to the patent (Murray and Stern, 2004; Sampat, 2005). Still other work, however, argues that biomedical researchers rarely if ever search to determine whether a prospective research project or experiment will infringe on patents (Walsh, et al., 2005; Lei et al., 2005). If researchers are (purposefully or otherwise) unaware of the existence of patents on a given area of research, what may cause them to shift their research agenda away from topics for which patents have been issued to other researchers?

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[14] "Largely as a result of the lack of federal funding for research, American Universities have become extremely aggressive in their attempts to raise funding from large corporations…..Large US based corporations have become so disheartened and disgusted with the situation they are now working with foreign universities, especially the elite institutions in France, Russia and China, which are more than willing to offer extremely favorable intellectual property terms." (R. Stanley Williams, HP Labs, September 17, 2002; statement reproduced at http://www.memagazine.org/contents/current/webonly/webex319.html; accessed April 2, 2005).

One explanation for these apparently conflicting findings hypothesizes that researchers are less likely to obtain essential research materials (biological materials or research tools) from other researchers when these materials are covered by patents. An instrument of growing importance in the governance of transfers of materials among researchers in both academia and industry is the "Materials Transfer Agreement" (MTA). MTAs are agreements among researchers governing the transfer and exchange of biological materials used in research. Their complexity and detailed provisions vary, but many of them include provisions for "reach-through" royalties on patents resulting from the use of the materials, and other such agreements limit the ability of the recipient of the materials to patent or license the results of research using the materials.

MTAs are used widely by both industry and academic researchers, and cover exchanges of materials within industry, within academia, and between industry and academia. If patented research results typically are associated with restrictive MTAs covering access by other researchers to these results, the findings of Murray and Stern and Sampat could be reconciled with those of Lei et al. and Walsh et al. In order for this explanation to be valid, patented research findings should be associated with the use of MTAs on exchanges of these or related research materials. With the exception of one preliminary examination of this possibility (Mowery and Ziedonis, 2007), the correlation between patents and MTAs has not been examined.

The exchange by researchers of biological materials for use in fundamental research has a long and occasionally controversial history in the biomedical sciences.[15] Such exchange has rarely been required by the terms of funding agreements with government agencies or other entities, but has instead been regulated by the Mertonian "norms" of scientific research, in which disclosure is paramount.[16]

[15] One celebrated controversy concerned the failure of the Gallo research team at the NIH to acknowledge that the pathbreaking isolation of the AIDS virus relied on a cell line established by another research team, at the Veterans Administration Clinical Oncology Branch (See Rubinstein, 1990 for further details). The Milstein-Kohler hybridoma technique for producing cell lines also was patented not by the discoverers but by another research team that requested and received a sample of the Milstein laboratory's plasmacytoma cells (See Wade, 1980).
[16] Nevertheless, reluctance to discuss research or share materials is far from rare among research scientists—35% of academic researchers surveyed in Campbell et al. (2002) concluded that withholding of materials or information increased during the 1990s, but 65% reported no increase in such restrictions on sharing. The survey found that roughly one-half of respondents had been denied access to materials by fellow researchers at least once in the 3 years prior to the survey, although overall, 90% of their requests were granted (about 12% of the survey respondents

Historically, materials exchanges were governed by little more than a letter from the source accompanying the materials, requesting acknowledgement and in some cases asking that the materials not be passed on to third parties (See McCain, 1990). The more elaborate MTAs used in contemporary materials exchanges appear to be a byproduct of the post-1980 surge in academic patenting.[17] Many MTAs used for exchanges of materials among academic researchers, especially those governing materials exchanges between industrial and academic researchers, now contain clauses requiring that the recipient of the materials surrender all claims to intellectual property based on discoveries using the materials (Marshall, 1997). In other cases, the source of the materials being requested has required a royalty on any commercial product resulting from research employing the material, a so-called "reach-through licensing agreement" (RTLA).

These provisions need not in and of themselves limit researchers' freedom or delay their access to important materials. But the overall increase in academic patenting of biomedical discoveries, as well as the higher perceived value of biological and genomic materials used in biomedical research, also have expanded the number and diversity of the institutions seeking to obtain or being asked to exchange these materials. The greater diversity of participants makes the negotiation of satisfactory terms among the parties to a given MTA more difficult, according to Eisenberg (2001),[18] and thus can delay researcher access to materials. These more elaborate MTAs appear to be more common in materials exchanges that span the academia-industry divide.[19]

Many university licensing offices also have become more active in overseeing the terms of MTAs for exchanges of research materials among academic researchers, and requirements for approval of their

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stated that they had denied requests from other researchers).

[17] Respondents to the survey of University of California agricultural biotechnology researchers by Lei et al. (2005) report "moderately more" use of MTAs than in 1999.

[18] The implications of a more diverse array of parties to these exchanges are complex, as the NIH Working Group on Research Tools (chaired by Professor Eisenberg) pointed out in its 1998 report: "The very term 'research tool' connotes a user perspective rather than a provider perspective. What a user sees as a research tool, a provider may see as a valuable end product for sale to customers." (NIH, 1998, p. 4).

[19] Consistent with this characterization, more than 73% of respondents to the survey by Lei et al. (2005) reported using MTAs for more than 60% of the research tools that they obtained from industry in 2004, while only 35% of respondents relied on formal MTAs for more than 60% of the research tools that they obtained from academic researchers.

terms may impose significant delays. Still another problem associated with the growing use of MTAs and their growing complexity is the demands on licensing office staff for review and approval. The director of the University of Pennsylvania technology licensing office noted in 1997 that that number of MTAs reviewed by his office had more than doubled during the previous 12 months from 197 to 425, even as the provisions of many of them had become more complex (Marshall, 1997). The NIH Working Group on Research Tools reported that the University of Washington's technology licensing office was dealing with an average annual volume of "incoming" MTAs (dealing with materials being requested by their institution's researchers) in the mid-1990s of roughly 1,000.

A recent paper by Walsh et al. (2007) reports the results of a survey of biomedical researchers who were asked about the constraining effects of patents and MTAs on their research activities. Consistent with the results in the earlier paper by Walsh et al. (2004), researchers reported that patents on relevant intellectual property did not significantly limit their research activities. But researchers did report that where their requests for research materials were not fulfilled, their ability to pursue research was constrained. The effects of denial of requests for materials were especially problematic for researchers working with "signaling proteins," a field characterized by high levels of academic patenting and considerable promise for lucrative applications in the pharmaceuticals industry. Walsh et al. (2007) provide no information on the extent to which MTAs typically covered transfers of research materials associated with patented research results, although as noted, they did find that failures to provide research materials were more pronounced for researchers in signaling proteins. The survey results also reported that more than one-quarter of the MTAs that were negotiated took more than one month to finalize. Data from the University of California, Davis technology transfer office indicate that MTAs with private-sector entities (either MTAs requesting materials from private-sector researchers or MTAs that furnish UC Davis research materials to industrial researchers) are much more likely to require more than 50 days to finalize (Figures 5 and 6).[20]

[20] These data exclude MTAs that are never finalized, and that failure in negotiations is also more likely for materials transfers to or from private-sector laboratories.

FIGURES 5 and 6 HERE

Considerable work remains to be done on the effects of MTAs on scientific communication, and on the relationship between patenting of university research advances and the use of MTAs. Little if anything is known about the prevalence of MTAs in nanotechnology research, although it seems plausible that they may play a significant role in the future development of this field of research for which new materials and access to highly specialized scientific instrumentation play such an important role.

The increased salience and complexity of MTAs within biomedical research also indicate the ways in which the growing assertion by universities of intellectual property rights may "spill over" and affect other instruments governing the disposition of inputs to, as opposed to the results of, scientific research. It is important to recognize that this increased assertion by universities of intellectual property rights in biomedical or nanotechnology research is not solely attributable to the Bayh-Dole Act; the other forces discussed earlier almost certainly would have produced a similar outcome in the absence of the Act. Nevertheless, the consequences of these trends for scientific communication and ultimately, for the productivity of the basic research enterprise within U.S. universities, are uncertain and merit considerable additional research. Moreover, the prevalence and effects of MTAs on nanotechnology research merit particular attention.

Vertical specialization in nanotechnology innovation

The structure of industrial innovation in nanotechnology in the "pro-patent era" also contrasts somewhat with that of innovation in previous U.S. post-1945 "new industries," particularly semiconductors and IT. In contrast to these industries, in which innovation initially was dominated by vertically integrated industrial enterprises that conducted fundamental research, developed new products, and manufactured these new products within a single organization (in many cases, producing the equipment needed to manufacture semiconductors or computer components), the current organization of commercial nanotechnology innovation resembles that of biotechnology. Firms specializing in research and very early-stage development (often, spinoffs from university laboratories) seek to license their products to established producers of related products in pharmaceuticals, medical equipment, or materials. In contrast to the vertically integrated structure of innovation in the early years of industries within the IT sector, nanotechnology innovation involves contractual and collaborative relationships among a number of "vertically specialized" firms that each specialize in one segment of the overall process of commercial innovation.

What is particularly noteworthy about nanotechnology, however, is the fact that vertical specialization appears to have characterized innovation in this technology from its inception. As I noted, the structure of innovation in nanotechnology more closely resembles that in biotechnology, for broadly similar reasons: Universities play a prominent role as sources of technological advances that (as noted above) are licensed, and university-based spinoff firms are an important source of entry into the industry. In addition, the strong intellectual property-rights environment characteristic of the current period favors the growth of "markets for technology," in which (relatively) clearly defined IP rights favor the use of contracts and markets for collaboration (Arora et al., 2001).

Economists long have emphasized the efficiency gains associated with firm-level specialization, and at least some scholars have argued that the development of vertically specialized industry structures supports higher levels of innovative performance.[21] But there are important countervailing factors that are unique to the innovation process, such as severe uncertainty about the true value or commercial prospects of a given piece of intellectual property, the potential for misrepresentation or opportunistic behavior within arms-length contracting relationships, and the ability of contracts to deal with a wide array of unanticipated contingencies in the process of taking fundamental research to the point of commercialization.

All of these factors may undercut the efficiency or innovative performance of vertically specialized structures, and these countervailing factors are likely to be more significant and pervasive in the early stages of a technology's development. Not only are technological and commercial uncertainty

[21] See Arora et al. (2001, p. 114): "…we strongly believe that such markets [for technology] can have substantial benefits by encouraging more extensive use of existing technologies and an increase in the rate of technological change…"

likely to be greatest in these early stages, but the parties to contractual agreements in the innovation process are likely to be less aware of the presence and implications of such uncertainties, and therefore less proficient at managing them. With the development of an industry or technology, these underlying uncertainties may be reduced and the ability of firms, inventors, and entrepreneurs to manage them may improve as a result of experience.

Most of the industries within IT now have shifted to a vertically specialized structure as well—in semiconductors, specialist firms are separately responsible for design of semiconductor components, while others specialize in production. The emergence of specialist producers of computer software and hardware has produced a similar structure of vertical specialization in the computer industry, which formerly relied on firms "bundling" software and hardware. The development of a vertically specialized industry structure in IT was associated with the emergence of "modular architectures," i.e., technological subsystems that have relatively stable interfaces with others, such as software and hardware within computers. But it is far too early for a similarly modular architecture to emerge within nanotechnology, and as a result, collaboration among specialized firms in innovation is likely to remain challenging.

It is far too early to reach any conclusions about the effects on innovative performance of the vertically specialized structure that characterizes nanotechnology R&D at present. Nevertheless, the recent experience of the U.S. biotechnology industry presents some cautionary evidence. As Cockburn (2004, 2006) has noted, vertical specialization within U.S. biotechnology thus far has failed to produce either significant overall returns for shareholders in biotechnology firms or a dramatic increase in the rate of new drug introduction by the large pharmaceutical firms that are primarily responsible for developing the drugs that biotechnology "R&D boutiques" specialize in discovering.[22] As Figure 5 shows, the

[22] "In general, one can be optimistic about efficiency being raised by increased vertical specialization in industries where competition is high among horizontal segments, where specialization reduces costs, where vertical coordination is relatively unimportant, where prices for the upstream technology accurately reflect marginal opportunity costs, and where bargaining and contracting are easy and effective.

Is this the case in early-stage pharmaceutical research? Several aspects of the economic relationship between biotech tool companies and Big Pharma suggest otherwise. Muted price signals from end users, high levels of uncertainty, high transaction costs and serious contracting problems, and limited competition in specific areas of technology all make finding an efficient vertically dis-integrated solution less likely….

number of new drugs approved annually by the U.S. Food and Drug Administration for commercial use declined significantly during 1994 – 2004, a period characterized by considerable expansion in the use by pharmaceuticals firms of alliances and vertical licensing arrangements, in the face of much higher levels of R&D spending within the industry. The interpretation of the data in Figure 7 is subject to considerable debate (e.g., counts of the number of new drugs approved for marketing say little or nothing about the therapeutic value or economic significance of individual drugs), and numerous other factors beyond the vertically specialized structure that has emerged within U.S. pharmaceuticals play important roles in these trends. Nonetheless, the fact remains that the growth of such a vertically specialized structure has not been associated with a significant increase in the (imperfectly measured) rate of innovation.

FIGURE 7 HERE

The emergence of a vertically specialized industry in nanotechnology is unusual at such an early point in the development of this technology and is related in a complex way to the interaction of several novel features of the environment surrounding innovation in nanotechnology—the changing role of universities as sources of patented technologies for license is closely linked with the broader shifts in U.S. intellectual property-rights policy that were discussed earlier. All three of these novel elements of nanotechnology within the U.S. national innovation system thus are interconnected, and it is difficult to single out any one as the cause of others.

Conclusion

Forecasting the pace and economic effects of the future development of nanotechnology is hazardous, as the 2006 report of the National Research Council's review of the NNI noted.[23] Among

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For economists, excess entry, high failure rates, and the inability to make profits are signs of overinvestment, "wrong prices," and misallocation of resources. Anecdotal evidence and the relatively low average stock market returns from biotechnology companies over the past few decades support this pessimistic view." (Cockburn, 2004, p. 20).

[23] "…efforts to analyze R&D's economic impact in other areas have often been hindered by a lack of metrics and lack of a comprehensive empirical framework…Assessing economic impact is also challenging because of the complexity of forces that drive economic growth and the inherent uncertainty surrounding outcomes observed at a particular point in time. Moreover, in general the timescales from research-based discovery to commercialization of technologies are long, often 20 years or more, and as an enabling technology, nanotechnology in particular is still in its infancy. The timescales over which the cumulative benefits of nanoscale R&D will become apparent will vary,

other things, any such forecast requires data that do not exist and further requires estimates of market demand and technical progress that are well beyond the capabilities of economists and scientists alike. Instead, this paper has attempted to examine the ways (if any) in which the current institutional structure and public policies within the evolving nanotechnology R&D enterprise represents a departure from longstanding characteristics of the post-1945 U.S. national innovation system. Although I believe that many of the current characterizations of this institutional structure as unprecedented are incorrect, there nevertheless are a number of aspects of the current structure of nanotechnology R&D that contrast with those of previous postwar innovations such as semiconductors, computers, and biotechnology.

One area of similarity among these innovations is in the characteristics of and motives for federal-government R&D funding. As I argued above, the majority of federal R&D funding throughout the post-1945 period has been directed to the support of government-agency missions or the support of specific policies, rather than the general advancement of knowledge. However eloquent his defense of basic research as a fountainhead of economic prosperity, Vannevar Bush's policy prescription (both his National Research Foundation and his broader justification for public funding) have not been the basis for the majority of the vastly expanded federal investment in R&D since 1945. Although the emphasis in much of the justifications for nanotechnology R&D on economic objectives may represent a change, the focus on specific policy objectives, as well as the cross-institutional collaboration that federal R&D programs encourage, is not novel.

Perhaps the most significant feature distinguishing nanotechnology from the IT-related innovations noted above is the very different environment of intellectual property rights that characterizes the post-1980 U.S. national innovation system by comparison with the IP environment that prevailed during 1945 – 1980. The strength of patentholder rights has increased, artifacts whose patentability was deemed uncertain or nonexistent now are patentable, and as a result, the rate of patenting overall and in

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depending on the nature of individual industries and products and the kinds of developmental research and testing required, such as clinical trials. Also, the investment needed for change and the availability of sustained investment for long-term gain will be determining factors. Although it is clear that nanotechnology will have an impact on many applications and industries, how to measure its economic impact is not now clear." (National Research Council, 2005, pp. 61-62).

nanotechnology in particular has increased significantly. Patents have been obtained by both academic and industrial researchers on a broad array of fundamental advances in nanotechnology in the very early stages of this technology's development, unlike the situation at a similarly early stage in the development of IT or even biotechnology.

Although U.S. universities have a long history of research collaboration with industry in applied topics, and their engagement with patenting and licensing can be traced back to the early years of the 20th century, the policy changes that have contributed to the "pro-patent era" have affected the channels through which many U.S. universities now seek to collaborate with industry and particularly, to transfer knowledge and technologies to industrial application. In spite of considerable evidence that patents and licenses may be relatively ineffective mechanisms for collaboration and technology transfer in fields other than chemistry and the biomedical sciences, U.S. universities have intensified their reliance on patents in nanotechnology R&D. The exclusionary power of nanotechnology patents has yet to be tested in the U.S. courts, which means that the value of these patents remains uncertain. But if the reliance on patents by academic researchers "spills over" into the use of Materials Transfer Agreements in nanotechnology R&D, as has been the case in much of biomedical R&D during the past 20 years, there is some risk that significant impediments to the conduct of fundamental science could arise. Here too, the changes in intellectual property policy and judicial treatment of intellectual property have interacted with institutional change within U.S. universities to produce a very different structure of university-industry interaction. Whether this "new wave" of patenting and licensing will prove efficient or effective, however, remains to be seen.

Finally, these changes in the form of university-industry interaction and intellectual property policy have combined to produce a structure for industrial innovation that contrasts with that observed in the early years of the IT sector and resembles more closely the structure that has emerged in biotechnology. This vertically specialized structure of innovation in a technology that is in its early stages of development and subject to enormous technical and commercial uncertainties, combined with the difficulties of writing contracts that can deal with unforeseen contingencies and opportunistic behavior, may have impeded the productivity of drug discovery and development within biotechnology. Whether vertical specialization in nanotechnology innovation will prove similarly difficult to manage is another area of uncertainty, albeit one with important implications for the future.

The U.S. national innovation system was remarkably stable in its essential characteristics for much of the post-1945 period, having experienced a fundamental structural transformation during the 1940-45 period (See Mowery and Rosenberg, 1993, 1999). Although many of the specific claims for nanotechnology as representing a fundamental transformation in the U.S. system are at best exaggerated in their details, the fact remains that the institutional nanotechnology R&D does differ from that of other post-1945 transformational innovations discussed in this paper. Will the institutional shifts observed in nanotechnology diffuse more broadly? And how will these institutional changes affect the pattern and pace of development of nanotechnology. As Bohr opined decades ago, “Prediction is very difficult, especially about the future.” But a closer monitoring of these institutional shifts seems indispensable to any assessment of the future development of nanotechnology and the future structure of the U.S. national innovation system.

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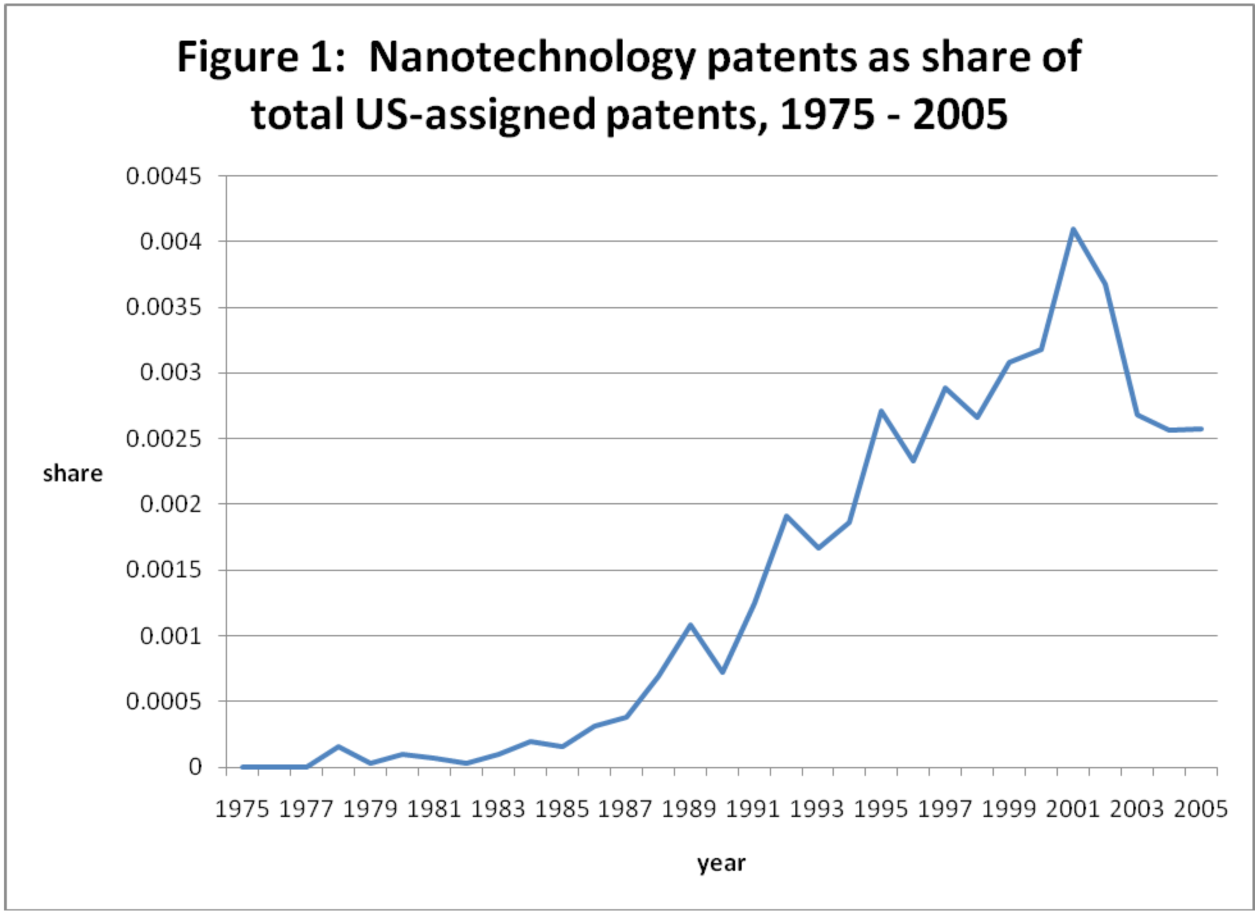
Figure 1: Nanotechnology patents as share of total US-assigned patents, 1975 - 2005
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year

Figure 2: Nanotechnolology patents as share of overall US university and corporate patenting, 1975 - 2005

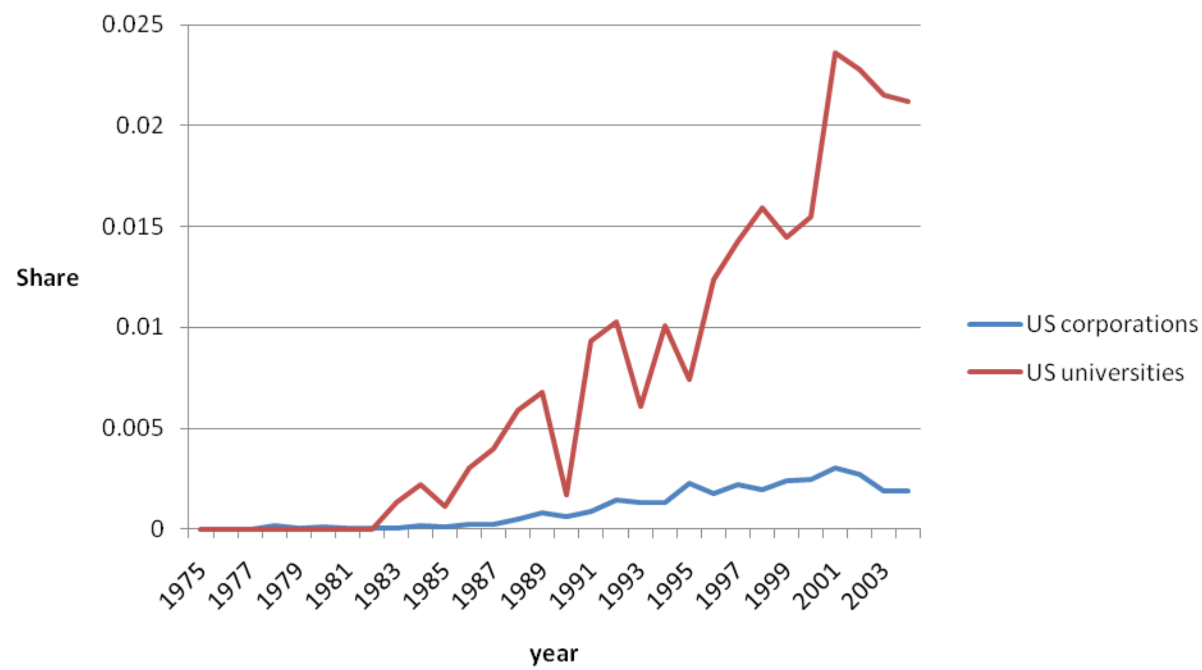


Figure 3: US research univ. patents % of all domestic-assignee US patents, 1963 - 99

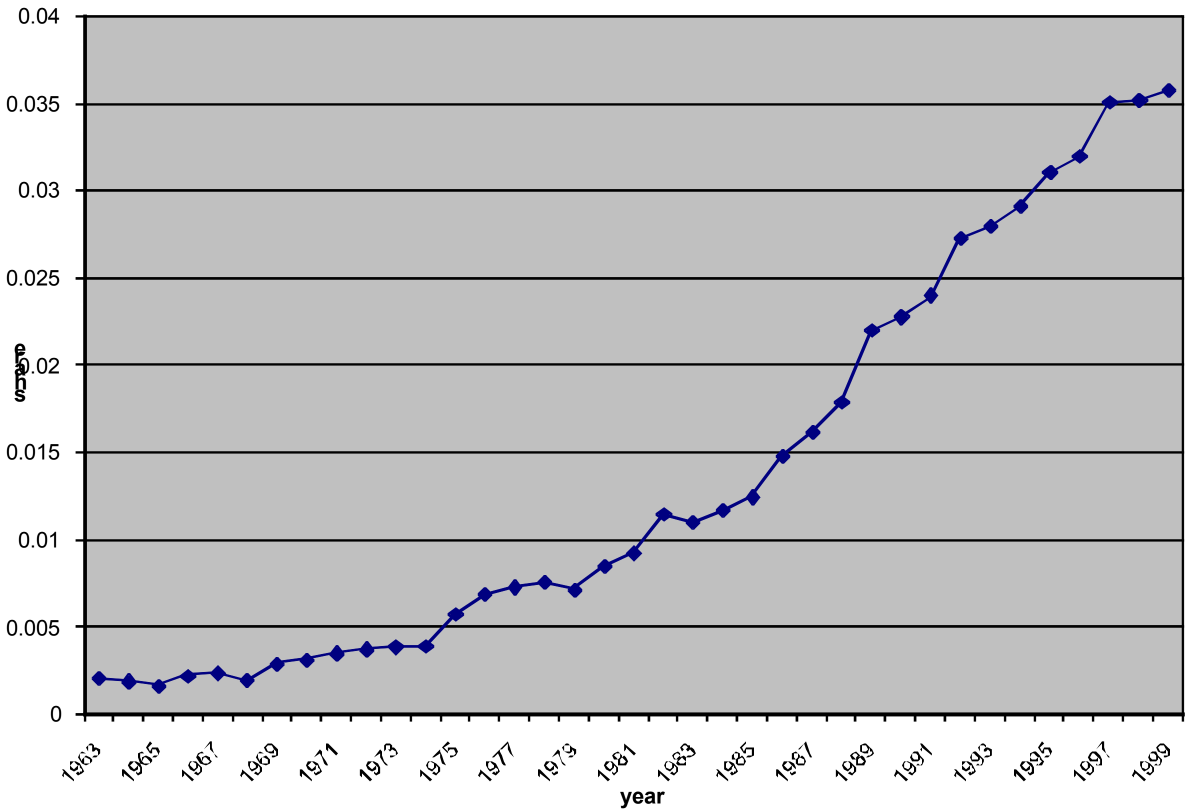


Figure 4: University Patents Per R&D Dollar, 1963-1993

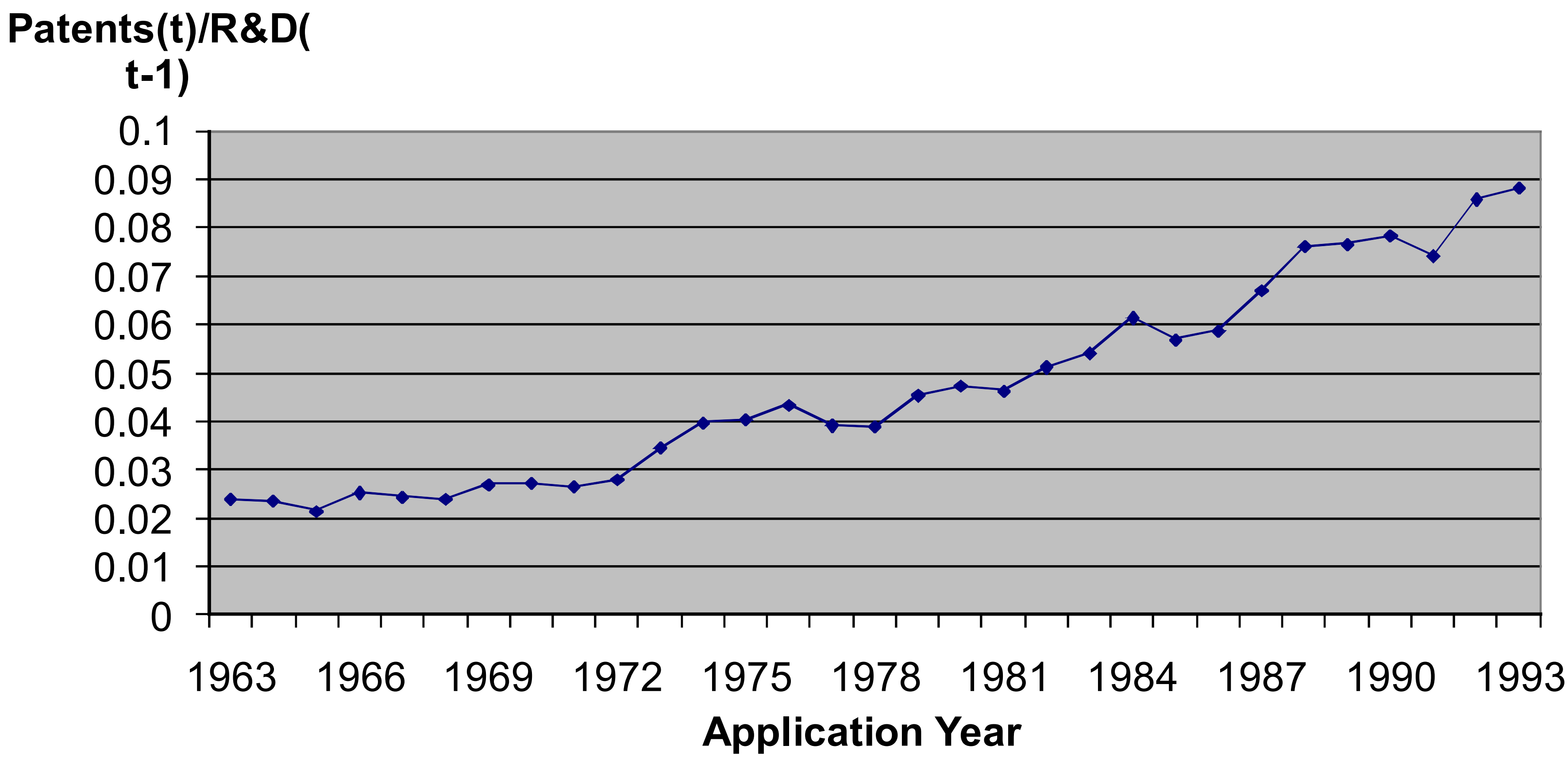


Figure 5

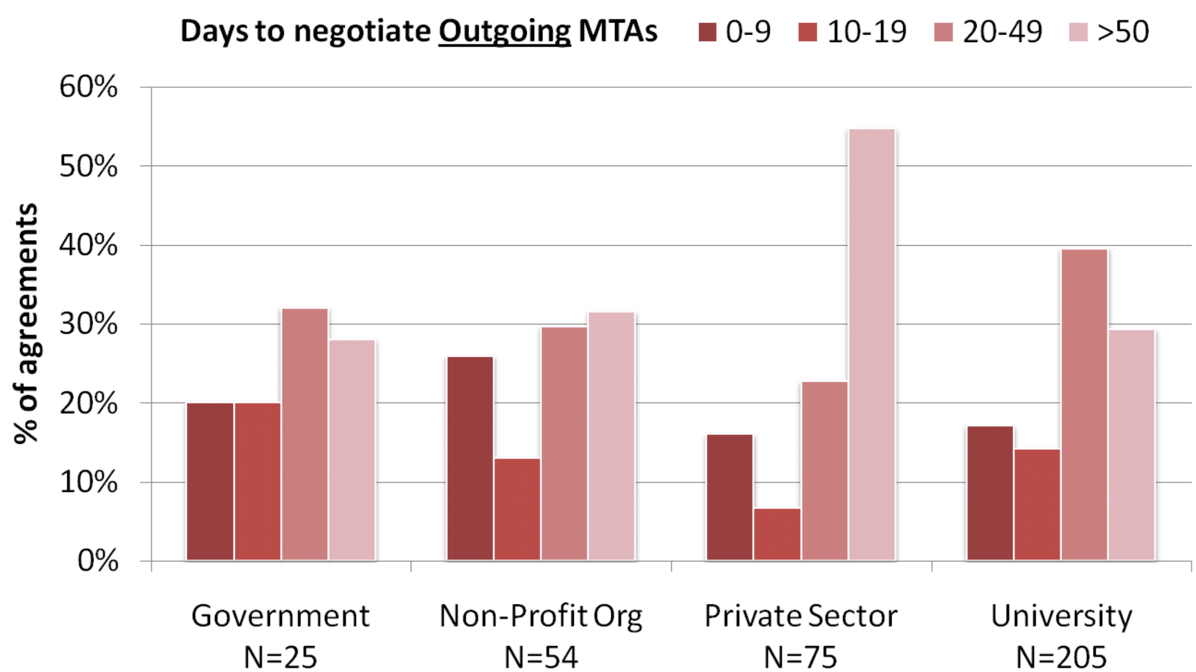

Days to negotiate Outgoing MTAs
0-9
10-19
20-49
>50
% of agreements
60%
50%
40%
30%
20%
10%
0%
Government N=25
Non-Profit Org N=54
Private Sector N=75
University N=205

Figure 6

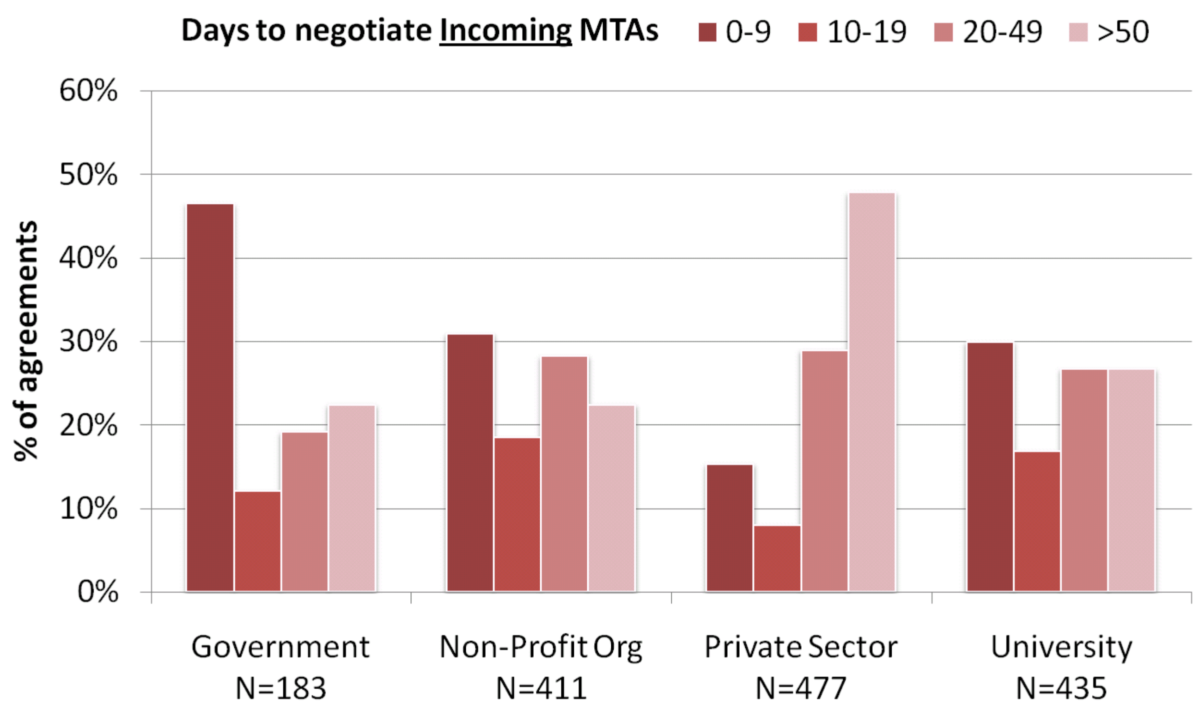
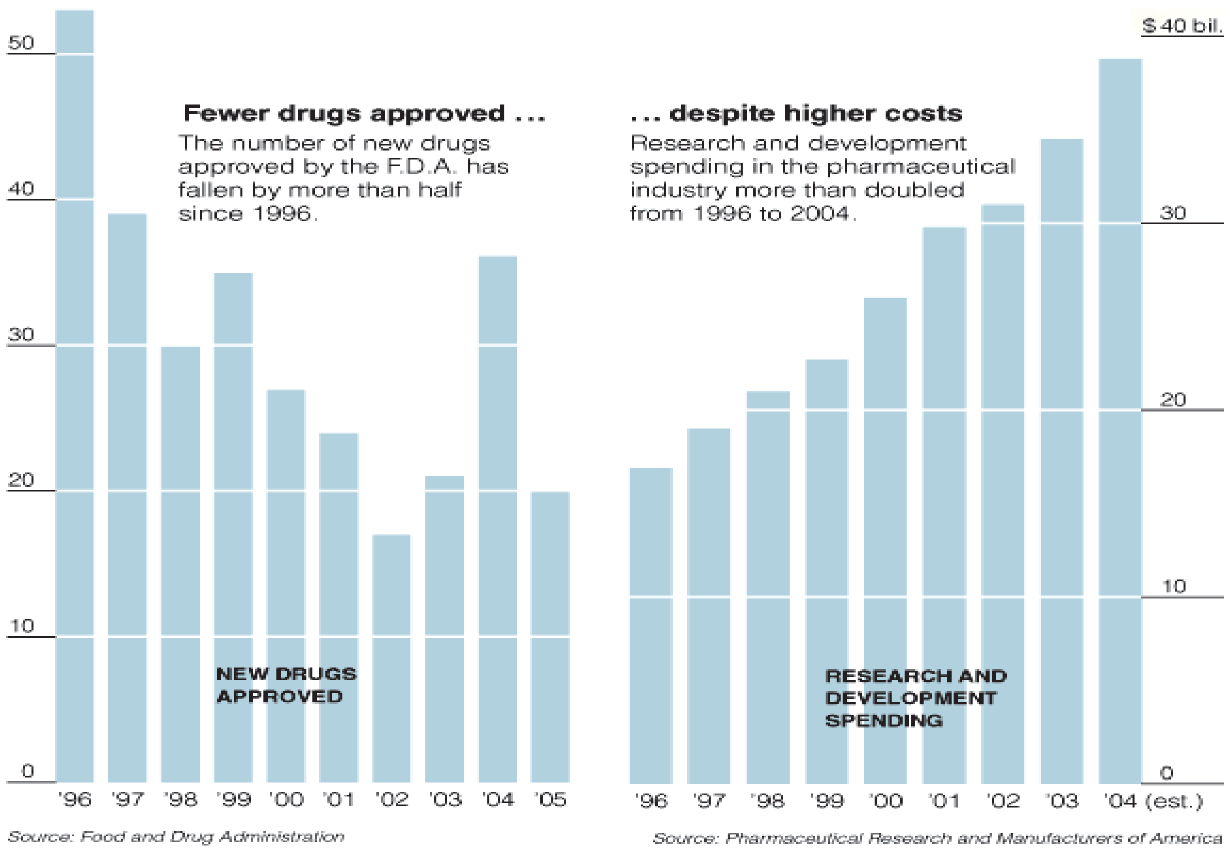

Days to negotiate Incoming MTAs
0-9
10-19
20-49
>50
60%
50%
40%
30%
20%
10%
0%
% of agreements
Government
N=183
Non-Profit Org
N=411
Private Sector
N=477
University
N=435

Figure 7



SOURCE: A. Berenson, "Drugs in 2005: Much Promise, Little Payoff," New York Times, January 11, 2006