For Knowledge and Profit:

University-Industry Research Centers,

Federal Science Policy and the Research University

Wesley Cohen and Richard Florida

Lucien Randazzese

October 1996

Oxford University Press, 1997, forthcoming

Table of Contents

Word Count: 56,852 words

ABOUT THE AUTHORS

Wesley Cohen is associate professor of economics and social science at Carnegie Mellon's Department of Social and Decision Sciences. He is also an affiliated faculty member in the H. John Heinz III School of Public Policy and Management and the Department of Engineering and Public Policy. His principal research interests concern the economics of technological change. He has published articles in numerous academic journals including the *American Economic Review*, the *Economic Journal*, the *Journal of Industrial Economics, Administrative Science Quarterly* and *Management Science*, among others.

Richard Florida is director of the Center for Economic Development and professor of management and public policy at Carnegie Mellon University's H. John Heinz III School of Public Policy and Management. He is currently a visiting professor at the John F. Kennedy School of Government. Florida is coauthor of *The Breakthrough Illusion: Corporate America's Failure to Move from Innovation to Mass Production* (Basic Books, 1990) and *Beyond Mass Production: The Japanese System and Its Transfer to the United States* (Oxford University Press, 1993).

ACKNOWLEDGEMENTS

This book summarizes the findings of a five-year study of university-industry research centers in the United States. The project's work was carried out by an interdisciplinary team of faculty members and graduate students at Carnegie Mellon University’s H. John Heinz III School of Public Policy and Management, Department of Social and Decision Sciences, and Department of Engineering and Public Policy.

In addition to the two principal authors, a number of people have made important contributions to this project. W. Richard Goe, an assistant professor in the Department of Sociology at Kansas State University, served as senior postdoctoral researcher on during the first two years of this project, and was principally responsible administration of the survey research. Lucien Randazzese, then a doctoral student in the Department of Engineering and Public Policy and Carnegie Mellon University and now a post-doctoral fellow in the Science, Technology and Public Policy Program at the Kennedy School of Government, was intimately involved in the analysis of the performance of university-industry research centers. Robert Gleeson, Associate Professor in the A.J. Palumbo School of Business Administration at Duquesne University and former executive director of the Center for Economic Development at Carnegie Mellon University, was responsible for research administration of the original Ford Foundation project. Mark Samber, a former doctoral student in he applied history program at Carnegie Mellon University and now a member of the Winthrop Group, prepared an initial background paper on

the history of university-industry research relationships which informed the development of Chapter 2 of this book.

Dozens of academics, business people, and government officials provided helpful comments and suggestions over the course of this project. While space precludes all those who commented on this work or contributed to our thinking on this subject, suggestions from the following people were especially helpful. We are particularly grateful to Harvey Brooks and David Hounshell for their detailed comments on earlier drafts of Chapter 2. Michael Best, Erich Bloch, Lewis Branscomb, Christopher Coburn, Paul David, Charles Fine, Robert Frosch, David Hart, Michael Intrilligator, Carlos Kruytbosch, Len Lederman, William Lazonick, Stuart Leslie, Richard Lester, David Mowery, Richard Nelson, Michael Piore, Rolf Piekarz, Walter Plosila, Edward Roberts, Daniel Roos, Eugene Skolnikoff, Don Smith, Paul Stoneman, Buzz Wilms, and Karl Willenbrock also provided helpful comments, suggestions, and information **[WES/LUCIEN ANY OTHERS YOU WANT TO ADD]**. Earlier versions of aspects of this work were presented at the 1994 annual meeting of the American Association for the Advancement of Science, and seminars at the National Bureau of Economic Research, Carnegie Mellon University, the Science, Technology, and Public Policy Program at Harvard University, UCLA, the MIT Industrial Performance Center, and the University of Massachusetts Lowell [**WES/ LUCIEN ANY OTHERS YOU WANT TO ADD]**. John Jankowski and Jennifer Bond of the National Science Foundation answered numerous requests for up-to-date data and

information, and provided helpful comments and suggestions as well. A number of current and former colleagues at Carnegie Mellon University, including Ashish Arora, Linda Babcock, Alfred Blumstein, Mark Fox, Davis Jenkins, Angel Jordan, William Kauffman, Sara Kiesler, George Loewenstein, Granger Morgan, Harry Paxton, Henry Piehler, and Ron Rohrer provided helpful comments and suggestions. Special thanks are due to David Arnold of the Ford Foundation and Len Lederman of the National Science Foundation for their financial support of this project. We would also like to thank Herb Addison, our editor at Oxford University Press for providing support, assistance, and encouragement. Over the course of this project, research assistance was provided by David Browdy, Margaret Deane, Paul Martin, Eaen McCarthy, Cathleen McGrath, and Phyllis Reuther. Sandra Salmonsen provided support in the editing and production of earlier versions of chapters 3, 4 and 5; and Yvonne Park produced the final versions of the tables and assisted in the editing of the final drafts of the manuscript.

The project was supported by generous grants from the Ford Foundation and the National Science Foundation with additional support from the National Academy of Engineering, Center for Economic Development at Carnegie Mellon University, and the Duquesne Light Company. The work was also supported by the various organizational units with which we are affiliated: the Heinz School, the Department of Social and Decision Sciences, and Department of Engineering and Public Policy at Carnegie Mellon University. The Science, Technology, and Policy Program in the Center for Science and International Affairs in the Kennedy School of

Government at Harvard University provided an institutional base and partial support for Richard Florida and Lucien Randazzese during the 1995-96 academic year.

CHAPTER 1

FOR KNOWLEDGE AND PROFIT

The communism of the scientific ethos is incompatible with the definition of technology as "private property" in a capitalistic economy. (Robert Merton, "The Normative Structure of Science," 1942).[1]

Some of the cultural differences that have long surrounded industrial research and university research have had the unfortunate effect of unnecessarily inhibiting the most effective interaction between industry and the universities. The notion that each sector has its own well-delineated and isolated role and that new knowledge would flow as rapidly as necessary and in one direction from the universities to industry is completely at odds with today's world. Today the pressure of international competition has introduced a critical time dimension into the system. The issue is not simply how much new knowledge is being generated but also how fast it is being translated into economically and socially beneficial products and processes. This argues for a much greater flow of information and especially of people in both directions between universities and industry. Despite recent gains in building linkages between U.S. universities and industry, there are still

> too many individuals in each sector who hold negative perspectives, attitudes and stereotypes with respect to the other sector. The nation cannot afford to have this situation persist. (President's Council of Advisors on Science and Technology, *Renewing the Promise: Research Intensive Universities and the Nation*, 1992).[2]

During the 1980s, the university was posed as a new and potentially potent weapon in battle for global economic supremacy, supplying industry with a source of technological breakthroughs with the promise of big commercial payoffs. Writing in 1981, then-president of Harvard University, Derek Bok argued that the university had a civic duty to ally itself more closely with private industry in an effort to counteract foreign competition and improve productivity.[3] At university after university, efforts were set in motion to show what academic research could do for industry, by drawing together talent in new research centers designed to attract corporate funding. Increasingly entrepreneurial academic scientists and administrators jumped at the chance to attract new research dollars. In December 1994, a front page story in the Sunday *New York Times* underscored the new reality with the headline, "The Big Stars on Campus Are Now Research Labs." The story made the point that competition for research funds has become so ferocious that some universities have engaged in "bidding wars" to attract not only star professors but entire research laboratories.[4]

Government science and technology policy contributed to the expansion of research relationships between the universities and industry, particularly university-industry research centers. During the 1980s, the National Science Foundation made joint research centers between universities and industry a cornerstone of its mission, establishing a host of new engineering research centers. The states launched efforts of their own to support collaborative research between universities and industry. Pennsylvania's Ben Franklin Partnership, Ohio's Thomas Edison program, the New York Science and Technology Foundation, the Michigan Strategic Fund, and New Jersey's Advanced Technology Centers are just the most notable examples of state programs supporting university R&D. By 1988, according to one study, some 43 states had initiated such programs with expenditures totalling $550 million.[5]

Joint research relationships between universities and industry have grown rapidly over the past two decades. Industrial funding of university research increased from $176 million in 1970 to $1.22 billion in 1993, as industry's share of academic research grew from 2.6 to 7.3 percent (see Figure 1-1).[6] At many top-tier universities, industry funding makes up a considerably greater share of total research funding. MIT, for example, receives more than 14 percent and Carnegie Mellon receives almost 20 percent of its research support from industry. A growing number of universities have set up offices and industrial liaison programs, designed to grant industry privileged access to their technologies. Washington University in St. Louis is one of a number of universities that allowed venture capitalists to establish an office on campus. Others, like Boston University, Harvard University and Carnegie Mellon became venture capitalists themselves, bankrolling high-technology start-ups in an effort to promote and to profit from new breakthrough technologies. Stanford University operates and maintains an expensive semiconductor fabrication facility, while other universities, like the University of South Carolina, built small manufacturing facilities on their campuses with the goal of turning new ideas into commercial products.

The universities also relaxed their rules concerning the commercial activities of their faculty and academic-industry relations. Many universities relaxed their rules governing the holding of patents and intellectual property by faculty members. Others simply looked away at potentially difficult situations, such as faculty using their laboratories to launch start-up or the growing restrictions on publication or information disclosure. In a striking development, Johns Hopkins University became the first university to allow faculty members and the university to take equity in companies, including new start-up companies, that sponsors their research, in essence allowing researchers or the university to trade research for stock.[7]

The universities registered considerable gains in the share of total U.S. research and development as a result of these actions. The university share of total research and development increased from 3 or 4 percent in the 1950s to almost 9 percent in 1970 and to nearly 14 percent by 1995 (see Figure 1-2). The universities performed $20.6 billion in R&D in 1993 - $10 billion more in real terms than they did in 1970.[8]

[Figures 1-1 and 1-2 about here]

By the early 1990s, however, much of the initial enthusiasm surrounding university-industry research relationships had faded. Originally promoted as a way improve American industrial competitiveness, generate new funds for academic research, and make the university research more relevant to industry's needs, these relationships are being questioned by academics who see them diverting the university from its core mission and by industry which views them as providing funds for long run basic research with little immediate commercial utility. For some, universities and industry possess different, and largely incompatible, values and incentives which can only lead to frustration and disillusionment on both sides.[9] Others believe that increased industry funding and influence over academic science calls into question the traditional values of open science. Still others contend that closer ties between universities and industry will result in reductions in the pool of fundamental knowledge over time with negative consequences for innovation and economic performance.

In his 1990 book, *Universities and the Future of America*, Derek Bok revised his views, calling closer ties between industry and the universities "something of a mixed blessing," adding that "contacts with industry create special dangers for the type of academic environment needed for basic research." Bok went on to say that such efforts have not proven to be an "effective strategy ... for allowing American companies to maintain a decisive lead over foreign competitors."[10] Concerns have been voiced by industry that competitiveness and industrial relevance provide too narrow a rationale for university research activities and are potentially damaging to academic science. In an influential 1993 article, John Armstrong, former vice president for science and technology at IBM noted that, "technology transfer from the university to industry has not been a major cause of our competitiveness problem. And, there are only a few sectors, for example, software development and perhaps biotechnology, where rapid technology transfer from university labs can have both a big and short term impact anyway. ... There is a danger that both society at large and those in the universities overstate what universities can contribute (because they are trying to maximize support) and therefor do foolish things to the university."[11] But, an even more ominous sign of the potential backlash against university-industry ties is the recent rise of more restrictive university policies toward academic-industrial relationships. In July 1995, for example, the University of Arizona prohibited members of its faculty from creating new spin-off companies based upon their academic research, citing the mounting legal entanglements over intellectual property and the attendant controversy over Ventana Medical Systems, a university-based spin-off company in which the university's venture capital fund had invested.[12]

KEY QUESTIONS

Deepening ties between university and industry pose a host of important questions for science and technology, economic growth, and American society. What is the appropriate tradeoff between the advance of academic science and the development of more applied technology of greater immediate relevance to industry and the economy? How do closer ties between university and industry affect the process of technological change and economic growth? How far should the university go in its efforts to attract industrial funds? What kind of access should universities grant to industrial partners? Can and should the university participate in proprietary research and weaken its long-standing commitment to the free flow of knowledge and ideas? How involved should the university become in the granting of intellectual property rights to private interests? What, if anything, should government do with regard to university-industry research relationships?

This book explores the changing nature of university-industry research relationships, the role of federal policy in conditioning those relationships, and their implications for academic science and the research university. Specifically, it reports the results of a five year research project on the scope, activities, and performance of formal university-industry research centers.[13] Such centers provide an important lens through which to view the evolving relationships among university, industry, and government, the changing nature and role of science and technology policy, the effect of such institutional and policy changes on technological and industrial progress, and their implications for both academic science and the research university. Indeed, the magnitude and diversity of these joint centers make them a fruitful *social experiment* of sorts for understanding the creation of new institutional and organizational arrangements among universities, industry and government. While we do not expect to answer all the questions surrounding university-industry research relationships, we do hope to answer many of them and to place the current debate in a rich factual context.

THEORIES OF UNIVERSITY AND INDUSTRY

The seminal work on the university is that of the sociologist, Robert Merton.[14] Merton argued that science should be an open enterprise, posing his classic distinction contrasting the quest for *priority* in discovery as the underlying motivating force for science with the profit motive of industry. While Merton spoke generally of science, his work is particularly relevant for academic science. Merton's view, which has often been described as a normative prescription, was grounded in efficiency. Firms are motivated to undertake scientific and technical advance in their quest for profit and intellectual property. Academic science has its own motivations that are centered on scientific understanding. The quest to discover and publish early creates a productive competition. New information is disseminated quickly. In the words of Herbert Simon, openness leads researchers to write their results on the "blackboard of science" promptly. The organizational scientist, Arthur Stinchcombe, has referred to the pursuit of academic science as a reputational economy.[1]

Building upon Merton's view, Paul David and Partha Dasgupta have presented an economic argument for keeping university and industry research largely separate.[15]

Building upon Merton's view, Paul David and Partha Dasgupta have presented an

economic argument for keeping university and industry research largely separate.[16] Academic science is a quest for fundamental discovery. Industry research focuses on profit motives and proprietary access. They argue that any intermingling of these functions would have negative social-welfare implications. In their view, closer university-industry relationships threaten the fundamental tenets governing academic research, including the free flow of ideas and the commitment to generating knowledge for public benefit. Dasgupta and David also argue that closer ties between universities and industry may drawn academic scientists toward applied endeavors of immediate relevance to industry and away from more fundamental scientific explorations which might yield breakthroughs of enormous benefit to society and economy. In their view, only a strong separation will optimize resource allocation and social welfare.

In contrast, Nathan Rosenberg has argued that the divide between science and technology is often difficult to discern. Applied work often begets fundamental work, and vice versa. Richard Nelson and Nathan Rosenberg recently wrote an historical paper chronicling this interaction.[17] They trace the ways in which university science contributes to technical advance in industry, and the ways in which technical advance in industry contributes to fundamental understanding. According to this perspective, university and industrial research are compliments, thus, greater academic attention to problems of relevance to industry in the short-run need not undermine basic research in the long run.

While such macro-level theories help illuminate the interaction of science and technology generally, they highlight only specific elements of the overall story concerning university-industry research relationships and tell is little about how the he individual and organizational incentives of the university affect collaboration with industry and the government.

Two theories tackle the university more specifically. One, associated with David Noble, created a considerable stir in the late 1970s and 1980s with its argument that corporations manipulate universities for their own ends.[18] The university, according to this strong corporate-control perspective, is little more than an unwitting pawn manipulated by industry. This view has been widely criticized. A second theory, espoused by Henry Etzkowitz and Roger Geiger, is that of the entrepreneurial university.[19] They argue that university faculty members and administrators act as entrepreneurs, cultivating opportunities for federal and industry funding and combining such funding in ways that advance their objectives.

Several empirical studies have examined the returns to university research and the nature of university-industry research relationships. In a study done for the National Science Foundation, Edwin Mansfield found that the social rate of return to academic research was roughly 28 percent for the ten-year period 1975-1985 and concluded that about one-tenth of new products and processes commercialized during that period capitalized on relatively recent university research, though Mansfield later revised his estimate downward to 20 percent.[20]

The widely-cited surveys of university-industry research relationships in the biotechnology and life sciences fields by David Blumenthal and his collaborators found that university and industrial research are complementary.[21] Blumenthal's original 1984 surveys of universities found that university researchers who received industrial funding were more productive than their peers in academic as well as industrial endeavors. His 1994 university study amended this finding somewhat, showing that while academic researchers with modest amounts of industrial funding remained more productive than their peers who did not have industry support, researchers who were dependent upon industry for a large share of their research support **[LUCIEN ADD EXACT PERCENTAGE]** were significantly less productive in terms of both academic and commercial performance.[22] As we will see, the complimentarity that Blumenthal discovered is somewhat unique to the fields of biotechnology and the life sciences more generally, and does not occur in other scientific and technology fields. Blumenthal's 1984 and 1994 industry surveys found that industry-supported research at universities generated returns in terms of patents, products and sales per dollar that were similar to those of industry's own research and development efforts. His 1994 industry survey found that industry depends on universities more for access to ideas, knowledge and talented potential researchers that for specific products or services.[23]

UNIVERSITIES AND THE PURSUIT OF EMINENCE

This is the backdrop against which our research was conducted. While our findings concur to some extent with the entrepreneurial university thesis of Etzkowitz and Geiger, we propose three important emendations to that view.

First and foremost, universities act to optimize eminence. Hence, the pursuit of external research support from industry and other sources essentially involves balancing new financial support against eminence. In most cases, attracting industrial support neither expands nor hinders the pursuit of academic eminence. However, industry funds may come with restrictions concerning the ownership of intellectual property, demands for secrecy and even control over publishing. Such restrictions can and frequently do constitute a direct cost to academic eminence. The relationship between eminence and industrial support varies considerably by scientific field. In some fields, eminence may be enhanced by close ties to industry, while in others such ties lead to levels of industrial control which hinder the pursuit of eminence. Strategies for attaining eminence have also changed over time. As Chapter 2 will show, in some periods, eminence dictated a focus on teaching; at other times it has advocated work to enrich the stock of knowledge.

Second, the university is engaged fundamentally in knowledge production, but the nature of that production has changed over time. In general, we have seen a shift in emphasis at universities from knowledge transfer in the 19th century, with an emphasis on training students who then go out into the world, to knowledge creation in the mid- and late-20th century. Today's research university has the advantage of being able to manage diversity better than most corporate research labs. The capacity to combine diverse approaches to research makes the university a particularly good place to pursue knowledge creation.

Third, we cannot understand this shift within universities without also understanding the rise and evolution of science-based industry in the late-19th and 20th centuries.[24] The beginning of this new form of production was marked by the rise of chemical and electrical industries at the turn of the century. As early as 1903, for example, MIT established a Research Laboratory in Physical Chemistry, followed in 1908 with its Research Laboratory in Applied Chemistry.[25] In 1920, MIT established the Division of Industrial Cooperation and Research, the predecessor of its current Office of Sponsored Programs, to coordinate its many interactions with industry and instituted its pioneering Technology Plan, the forerunner of contemporary industrial liaison programs, to attract industrial sponsors. In 1911, the Mellon Institute was established with close links to the University of Pittsburgh and later to Carnegie Mellon University to conduct applied research in physical chemistry and chemical engineering for science-based firms located in and around Pittsburgh. Today the life-sciences and molecular biology best represent the contemporary profile of science-based industry. The growing emphasis on the role of knowledge in production has focused attention on the important contribution that universities might make to industry today.

UNIVERSITY-INDUSTRY RESEARCH CENTERS

These general points are based on a detailed study of what we refer to as university-industry research centers (UIRCs). Our research had three components. We first contacted universities to identify UIRCs. We then distributed surveys to the UIRCs he had identified. Finally, we interviewed firms that have funded UIRCs to get their impressions.

Past research had been mainly limited to case-studies, focusing either on a single university or a single university-industry linkage, or to studies of specific fields of science and technology, for example, Blumenthal's 1984 and 1994 surveys of biotechnology and life sciences respectively. Two 1994 studies by Robert Morgan and Diane Rahm, conducted while our research was in progress, did examine university-industry research relationships across a broader number of fields.[26] No one however examined the performance and implications of formal university-industry research relationships across the entire range of scientific fields.

Our research focussed on the scope, performance and academic implications of formal university-industry research centers. To compile the sample of university-industry research centers, the National Science Foundation provided us with a list of universities that received industrial funding. We then asked university administrators to identify faculty relationships with industry. We quickly found that they could only identify the most formal of these links. Consulting relations, for example, were nearly impossible to fully identify. We decided to focus our search. This meant focusing on large-scale, official collaboration: university-industry research centers, or what we refer to as "UIRCs."

We set formal criteria for identifying UIRCs. First, the research center had to receive at least $100,000 in outside funding per year. We felt that any less was unlikely to support a real center. And, some part of the funding, however small, had to come from industry. This could mean as little as 1 percent, and it could come from a single company.

We sent faxes to 437 universities that NSF identified as receiving industry support. We asked them to identify research centers on campus. Many, including MIT, did not initially want to respond. After some persistence, we were able to get responses from 92 percent of the universities we contacted. Together they identified 1,466 research centers in the United States. After surveying these centers more closely we determined that 1056 centers, located at 203 universities nation-wide, met our criteria for a UIRC. The number was surprisingly high; more than half had been established in the 1980s.

Of the UIRCs we identified, 511 (48.5 percent) answered our detailed survey. Based on their responses, we estimate that UIRCs in the United States spend $4.12 billion annually, with $2.89 billion focused specifically on research and development. In 1990, the year for which the survey data are relevant, this was equivalent to almost 18 percent of total national spending for academic science and engineering R&D. Science and engineering R&D in 1990 received $1.73 billion from the National Science Foundation, $9.16 billion from all federal sources, and $16.3 billion from all sources, public and private. The remainder of UIRC budgets, roughly $1.4 billion annually, went to administration, technical service, training, education, and economic development.[27] These university-industry research centers are concentrated in high-technology fields such as software, advanced materials, biomedical and biotechnology, and environmental technology.

UIRCs involve not only a lot of money, but also a large number of faculty and students. They include, according to our survey, 19,000 university faculty members, 29,600 doctoral-level researchers, and 27,000 graduate students. These people do not necessarily work for UIRCs full-time. We find that many of these researchers do not have to be paid for out of center funds. Rather, centers are able to leverage faculty, graduate and researcher efforts which are remunerated by the university.

This leveraging poses a difficult problem for measuring UIRC productivity. Early in our analysis it looked like smaller centers were more productive, measured in terms of patents, inventions, and licenses per dollar of R&D spending.[28] The finding was preliminary, but federal policy makers clearly wanted to believe it. On further analysis it proved false. Consider this extreme example: centers that pay for only 2 percent of a faculty member's time might claim all of that faculty member's achievements. This bias made smaller centers appear more productive, because larger centers simply tended to pay for a greater percentage of faculty time. As Chapter 4 will show, once we measured the level of effort associated with centers more accurately, small and large centers appeared equally productive.[29]

UNIVERSITY INITIATIVE AND GOVERNMENT POLICY

A main conclusion of our work is that the main initiative for university-industry research centers originated with universities. More than three-quarters of centers in our survey report that the main impetus for their establishment came from the entrepreneurial efforts of university faculty an administration. These entrepreneurial efforts on the part of universities have been prompted by real declines in per capita support to university research, expectations of further cutbacks in government support for academic research in the future, and changes in federal funding programs which require industrial matching funds to be eligible to participate in key government science and technology programs. This provides additional support for the entrepreneurial university view and a rather strong rebuttal of the corporate manipulation thesis.

This university initiative was, however, a response to shifts in government policies. Roughly 60 percent of this funding comes from government. This amounts to either to 45 percent or to 60 percent of total UIRC funding, depending on how government funding is weighted. The federal government funds roughly two-thirds of this total, state governments one-third. Of the UIRCs surveyed, 86 percent receive government support, 71 percent were established based on government support, and 40 percent feel they could not continue without this support.

Two new legislative initiatives conditioned the move among universities toward UIRCs. First, a change in the tax law in the 1980s [**LUCIEN/ WES IS THIS THE STEVENSON WYDLER ACT]** enabled companies to deduct contributions to academic research including university-based research from which they would directly benefit. Second, the Bayh-Dole Act enabled universities to take patent positions on findings from government funded research. Coincident with these changes in federal policy, government agencies began funding a relatively small number of university-industry research centers, such as the National Science Foundation Engineering Research Centers and Science and Technology Centers. These initiatives fostered the perception that new government resources would be increasingly tied to university-industry joint research initiatives.

The push for closer university-industry ties had its roots in concerns about declining U.S. competitiveness in the 1980s. Erich Bloch promoted joint university-industry research centers from his position as Director of the National Science Foundation: Bloch had initially developed this idea at IBM, and believed closer proximity of university and industrial research would promote increasingly relevant inter-disciplinary research and contribute to improved industrial competitiveness. Although less than 100 such centers were originally funded, it suggested that universities seeking federal research grants should cultivate links to industry. This created the perception that future competitions for federal funds - and the future pursuit of eminence - would increasingly be tied to university-industry centers, prompting universities across the country to establish such centers sometimes with their own funds. The universities in our study, for example, provide 14 percent of the total support for the UIRCs in our survey, much of it coming in the form of cash support.

INDUSTRY'S CHANGING VIEWS

Industrial funding of university research has increased dramatically over the past two decades, and a significant portion of UIRC funding. Industry, for example, provides more than $560 million to support the university-industry research centers in our sample. This represents half of industry's total contribution to academic research, even though it is only one percent of all industrial research and development spending. In this sense, university-industry research centers may represent a key mechanism for attracting increased support from industry.

We conducted interviews with industrial R&D managers at science-based companies that participate in UIRCs. Almost every industry official we interviewed thinks that universities perform their traditional roles very well. Cutting-edge academic research is superb, and students are being well educated. Companies did express a variety of concerns, however, when it came to university involvement in more applied research and development endeavors, in particular through formal university-industry research centers.

First, industry is concerned that UIRCs are leading university scientists to redirect their research from the pursuit of fundamental science into more applied areas. Industry worries that this may reduce the stock of basic knowledge from which they draw, and which they would find impossible to replace. Industry believes that it can generate all the applied research it needs.

Second, industry feels that it can more efficiently obtain useable research results out of one-on-one interactions with professors. UIRCs offer the advantage of strong government support. This often allows firms to achieve leverage government and university investments in university research. But overhead in research centers is often high, and the results may not be directly relevant to the interests of the participating company. Faced with increasing pressure to achieve results, company research divisions are resorting to smaller contracts with single faculty that last several years. This ensures them faculty commitment, a counterpart with aptitude for the business culture, and a check on overhead costs. One vice-president for research summarized industry's feelings about UIRCs: "The university takes this money, then guts the relationship."

Third, industry is concerned about, and often frustrated by, its dealings with the university over intellectual property issues. Many of the industry officials we interviewed expressed frustration at not being able to negotiate suitable intellectual property arrangements with universities, particularly that universities often insists on retaining ownership of intellectual property. Companies are also concerned that the UIRCs they support will share vital information with other competing companies. Because several firms normally participate in a single research center, faculty members may inadvertently make public vital information. For industry, this risk of information leakage is significant.

BALANCING EMINENCE AND INDUSTRIAL SUPPORT

University-industry research centers pose important implications for academic science and for the research university. For universities, the key issue has to do with the tradeoff between their traditional academic roles and the quest for eminence on the one hand, and the pursuit of funding support from industry on the other.

A growing number of commentators contend that increasing industrial funding is corrupting the very essence of academic research by placing restrictions on what can be published and how communication can take place within universities. Others are concerned that increasing industrial support of academic research is causing a shift from basic to more applied research, essentially consuming the seed corn of the American science and technology enterprise.

The restrictions that industry places on UIRCs may subvert the traditional ethos of the university and the efficient pursuit of academic science. This risk is not new. The initial wave of research center growth appeared at the turn of the century in conjunction with the rise of industrial R&D. As the next chapter will show, chemistry and engineering departments at the time were host to a deep struggle between faculty who wanted to pursue applied, industry-oriented research, and other faculty who wanted to study anything so long as it was basic research. Departments that allowed industry to define their research agendas or impose restrictions on faculty members lost eminence as prestigious faculty members moved away. One goal of post-war government funding for university research was to counteract this negative impact of industrial support by creating `steeples of excellence.'

Our survey of UIRCs indicates that industry continues to affect the direction of research agendas, their policies on information disclosure and publication, and, perhaps most troubling, the amount of communication within the center itself. As Chapter 6 will show, 65 percent of the centers we surveyed indicated that industry exerts a `moderate to strong influence' over the direction of their research. Over half of the centers said that industry could force a delay in publication, and over a third said that industry could have data deleted. Admittedly, government research funding is not immune from restriction, but as Chapter 2 will show, the typical extent of government restrictions even on classified research is much less than that of industry. While prestigious universities with strong federal funding are often able to avoid the delirious impact of industry investment, lesser research universities are not.

The dilemma is that more restrictive conditions within the research center appear to generate more commercially viable technology. Thee centers that responded to our survey alone produce 20 percent of the patents from universities as a whole, generating patents at roughly one-third the rate of industrial research laboratories per dollar of R&D spending. As Chapter 5 will show, UIRCs make an even more important contribution to industrial innovation by providing new ideas for industrial research projects, suggesting new avenues for product or process improvements and by making ongoing industrial research more efficient. And, UIRCs provide companies with a window on new technology - a means by which firms can obtain information on outside sources of science and technology.

In contrast to David and Dasgupta's argument that important developments tend to arise from autonomous science, we find that UIRCs can generate significant social welfare gains by creating industry-relevant technology more efficiently. But this efficiency comes at the cost of traditional notions of the nature of academic science. In other words, UIRCs may create a tradeoff between short- and long-term goals.

The exception to this tradeoff is in biotechnology. UIRCs in this field manages to maintain a high commercial impact while pursuing excellent academic science. The main reason has to do with the relatively unique nature of the technology involved. There is a particularly close link between scientific advance and commercially-relevant technology of direct use in industry in this field - a link which is also evident in the large presence of eminent academic scientists within leading biotechnology companies, particularly university spin-off companies.

This brings us to another central point of this book. Throughout this book, we emphasize the fact that UIRCs and university-industry research relationships are not homogeneous. Rather, these relationships are defined by diversity and heterogeneity. The performance of UIRCs, for example, differs considerably by academic discipline, field of technology, and the goals and objectives such centers pursue - so too does the trade-off between academic norms and industrial performance. Furthermore, centers which choose to work more on industrial applications are more productive in producing outputs of relevance to industry. These centers, however, spend less time and effort on traditional academic research activities. The result is that they generate less traditional academic output such as papers and advanced degrees.

Finally, it is worth pointing out that whereas universities used to comprise only faculty and students, they now employ large numbers of research scientists. These research scientists work primarily on sponsored research, are outside the tenure track, and can be considered a distinct group within the university community. Carnegie Mellon, for example, has created a separate career track for research scientists. Research scientists may heighten the tension between eminence and industrial support, by shifting academic research in a more applied direction. Our findings support this conjecture, indicating that centers with many research scientists conduct more applied research. Research scientists may thus play an increasingly important role in the trade-off universities face between traditional academic eminence and the pursuit of applied R&D of the sort that attracts industrial funding.

CHAPTER OUTLINE

To shed light on these issues, this book explores the magnitude, activities and effects of university-industry research centers. Emphasizing the tension between their traditional academic roles and quest for eminence on the one hand, and the pursuit of industrial support, we begin by discussing the historical and institutional factors that have shaped the origins and evolution of university-industry research relationships. We then turn to the scope, activities and performance of current-day university-industry research centers, their effects on industrial and academic performance, and they implications they pose for academic science and the research university.

Chapter 2 provides an historical and institutional context for our discussion, providing an historical review of the origin and evolution of research relationships between the universities and industry. This chapter highlights the tension between eminence and industrial support. It also emphasizes the role of university initiative in structuring early relationships with industry, and highlights the role played by both direct and indirect government policies in illustrates the role of government policy in shaping evolving university-industry ties, particularly in the period after World War II. This chapter begins with the origins of such relationships in the late nineteenth and early twentieth centuries alongside science-based industry and traces their evolution through the Cold War era in American science and technology. It then examines the deepening ties between industry and university since the 1970s and outlines the types of relationships forged, from major industry-funded research centers and university efforts to patent and license technology to attempts by universities to launch start-up companies and take part in venture capital activities. This chapter also tracks increasing industrial funding of academic science over this period and discusses the role played by government science and technology policies in catalyzing and facilitating greater interaction between university and industry.

Chapter Three turns attention to the current state of university-industry research centers, providing detailed information on the scope, magnitude, and activities of these centers. How extensive are university-industry research centers? How much is spent on them? How many universities participate? In what fields are UIRCs concentrated? What are their major sources of funding? This chapter provides new and unique data on the magnitude and extent of university-industry research centers and their sources of funds, documenting the rapid growth of such research centers in recent years. This chapter also highlights the interaction between university initiative and government policy in the formation of UIRCs.

Chapter Four examines several aspects of the performance and productivity of UIRCs. It focusses on the role of university-industry relationships in the process of technological change, in particular on the ability of UIRCS to generate both academic and commercial innovations. This chapter presents our analysis of the industrial and academic performance of UIRCs. It suggests that universities can and do make direct contributions to technical advance in industry by generating patents, licenses, and product and process innovations of use by industry. It also suggests that UIRCs also have a series of intermediate effects on the industrial innovation process, generating new ideas which suggest product and process improvements to industry and which make industrial R&D more efficient. It examines the way that factors such as discipline, technology, goals, and size affect the performance of UIRCs. Here, we emphasize that the performance and productivity or university-industry research centers varies considerably by scientific and technological field. This chapter also presents the findings of interviews conducted with industrial participants in UIRCs.

Chapter Five discusses the implications that deepening research relationships between universities and industry pose for academic science and for the university more broadly. It revisits the tension between the quest for eminence and the pursuit of industrial research support, utilizing empirical data from our survey of UIRCs. Some have argued that joint centers between universities and industry pose a fundamental challenge to the basic tenets and norms that have governed university research over the centuries. This chapter tackles these issues directly, providing detailed data on the implications of such centers on academic science and the university's research mission. It discusses industry's ability to direct the research agenda and the granting of intellectual property rights by universities. It examines the critical issues of information restriction, publication delay, data deletion, and the conduct of more applied R&D at UIRCs. It also examines the effects of these departures from the academic norm on center performance -- both academic performance and more commercially relevant performance. It suggests that industry funding of and participation in university research pose an important tradeoff for society.

Chapter Six concludes the book with a summary of the main findings of the research and a more general discussion of the future of university-industry research relationships and their relevance for public policy. What is the trajectory of university-industry research relationships? Are they still growing, or have they peaked and are beginning to wane? What kinds of changes are likely to occur in these relationships? What are their implications for industry and academia? Do university-industry research centers represent a shift in the nature and structure of relationships in the American system of innovation or are they evidence of the resilience of these relationships? What do various sorts of changes in government science policy imply for the future of university-industry research relationships? What is the future of the relationship between universities, industry and government?

Chapter 2

Eminence, Research, and Industrial Support:

Origins and Evolution of University-Industry Research Relationships

> The place in men's esteem once filled by the church and state is now held by pecuniary traffic, business enterprise. So that the graver issues of academic policy which now tax the discretion of the directive powers, reduce themselves in the main to a question of the claims of science and scholarship on the one hand and those of business principles and pecuniary gain on the other. In one shape or another, this problem of adjustment, reconciliation or compromise between the needs of higher learning and the demands of business enterprise is for ever present in the deliberations of the university directorate. This question gathers in its net all those perplexing details that now claim the attention of the ruling bodies (Thorstein Veblen, *The Higher Learning in America*, 1918).[30].

WES/LUCIEN: PROBABLY NEEDS A NICE PARAGRAPH OR TWO OPENING THIS CHAPTER

This chapter examines the evolution of research relationships between universities and industry over the course of the past century, and in doing so it provides an historical context from which to view our more focussed and empirical analysis of present-day university-industry research centers. It begins by exploring the rise of research connections between universities and industry alongside science-based industry in the late nineteenth and early twentieth centuries and traces the evolution of those connections through the Cold War era in American science and technology and to the present day. As Nathan Rosenberg and Richard Nelson have noted: "It is striking that the present discussion focuses so closely on the here and now; there is very little examination of the role traditionally played by American universities or of how these roles have evolved. ... Thus, the current debate is proceeding with little grounding in what is actually going on now, and why and how we have arrived at our present predicament."[31]

But before proceeding to the particulars, it is useful to highlight three main threads or lessons that run through the evolving relationships between university and industry in American society.

First, our review of the historical record indicates that present-day university-industry research centers are the product of a nearly century long process of organizational evolution. Corporate funding of university research originated more than a century ago alongside the rise of science-based industry during the late 19th and early 20th centuries. The beginning of this new form of production was marked by the rise of chemical and electrical industries at the turn of the century and is evident today in the biological sciences. The initial wave of research center growth appeared at the turn of the century in conjunction with the rise of industrial R&D. The universities also developed specialized programs to train engineers for industry in the latter half of then nineteenth century, and by the opening decades of the twentieth century industry looked to the universities to provided research scientists for its newly founded R&D laboratories. Contemporary university-industry research centers emerged from this nearly century long process of organizational experimentation and evolution.

Second, the historical record highlights the role of university initiative in the establishment of joint research relationships with industry. Our review of the historical evidence indicates that the university itself has been the prime actor in forging relationships with industry. The present day relationship between the universities and industry is in large measure the result of university initiative to cultivate and attract support from industry. This chapter thus provides support for the entrepreneurial university view advanced by Henry Etzkowitz and Roger Geiger[32] and a rather strong rebuttal of the corporate manipulation thesis associated with David Noble.[33]

Third, our historical analysis illustrates the role of government in structuring and conditioning the relationships between American universities and industry. If university initiative provided the immediate impulse behind university-industry research relationships, government policies operate as a fundamental cause. From the Morrill Act of 1862 to the mobilization efforts for the two world wars, through the Cold War era, and up to the more recent debate over the role of academic science in national economic competitiveness, government policy has conditioned the relationship between the universities and industry. In this chapter, we distinguish between polices which provide direct incentives for university-industry research relationships such as government funding policies which stipulate joint ties and indirect policies such those affecting university patent holdings and intellectual property right. We also distinguish between the intended and unintended consequences of government policies. In fact, one consequence of the massive increase in post-World War II government funding for university research was to counteract the negative impact of industrial support by creating new source of support for the pursuit of more or less unfettered scientific research.

As this chapter will show, the recent resurgence of university-industry research relationships between universities and industry, and university-industry research centers in particular, stems from three significant change in government policies during the 1980s. First, a change in the tax law in the 1980s enabled companies to deduct contributions to academic research including university-based research from which they would directly benefit. Second, the Bayh-Dole Act enabled universities to take patent positions on findings from government funded research. Third, government agencies began funding a relatively small number of university-industry research centers, such as the National Science Foundation Engineering Research Centers and Science and Technology Centers. These initiatives fostered the perception that new government resources would be increasingly tied to university-industry joint research initiatives.

Fourth and perhaps moss significantly, the historical record illuminates the tension between the eminence and the pursuit of industrial support. University strategies for attaining eminence have changed considerably over the past century. During the 19th century and before, eminence was the product of excellent teaching and a distinguished and learned faculty. Scientific research became a key vehicle for eminence only during late 19th and particularly over the course of the 20th century. The use of industrial support to pursue research eminence is a delicate balance. Industrial support for research does not allow unfettered pursuit of science, but typically involves a more targeted search for innovations and scientific advance of relevance to industry. More problematical from the standpoint of academic eminence, research supported by industry frequently entails restrictions on information disclosure and publication. Such restrictions not only subvert the traditional academic ethos of the university, but may hinder the pursuit of eminence by causing the scientific reputations of departments to decline or if they result in departures of key scientists. As this chapter will show, the tension between eminence and industrial support emerged with the initial wave of university-industry research center formation during the early 20th century. Chemistry and engineering departments were the source of struggles between faculty who wanted to pursue applied, industry-oriented research, and other faculty who wanted to study anything so long as it was basic research. This tension ran particularly deep at MIT. Departments that allowed industry to define their research agendas or impose restrictions on faculty members lost eminence as prestigious faculty members moved away.

Research and Eminence

While research is the main source of eminence for the contemporary university, it is important to recall that this was not always the case. While the university's status as a research institution is now virtually taken as a given, it is important to recall that university involvement in research is itself a fairly recent phenomenon. Until the twentieth century, the main mission of the university was education. Indeed, in *The Emergence of the American University*, Laurence Veysey remarks that the American *research* university of the early twentieth century bore only limited resemblance to its more genteel, teaching-oriented counterpart of the Civil War period and before.[34] It was only with the rise of modern, science-based industry in the late nineteenth and twentieth centuries that the university became involved in systematic research in science and engineering.

The oldest and most important locus of university-industry relationships has been consulting relationships. Professors have longed served as consultants to technologically-advanced industries, particularly in science-based industries such as chemicals and pharmaceuticals. Professors have also at times held significant private patent polls which they have licensed to industrial firms. But, consulting relationships have tended to occur outside the formal context of university-industry relationships. Consulting arrangements are to a large degree private relationships between firms and individual professors which occur outside and independent of the university. Furthermore, universities have developed formal policies covering the consulting activities of their faculties. Professors, for example, are typically limited to consulting "one day per week."

Our main interest here is in the emergence and evolution of formal ties between universities and industry, in particular formal ties which involve the joint funding and pursuit of scientific research and technological innovation in the particular institutional context of the university. It is here that we note the tension between eminence and industrial support which lies at the heart of university-industry relationships.

The tremendous growth of American industry during the late nineteenth and early twentieth centuries, provided a new source of financial support for universities. As early as the 1850s, industrialists made significant gifts to leading universities such as Yale and Harvard, leading to early controversies over "who controls the university's agenda." During the 1880s, Corning funded research by the physics department at Cornell University. Edison engaged the physics departments at Princeton University and Johns Hopkins University to do studies to support his work on electric lighting and power.[35] n the wake of the financial panic of 1893, a number of universities stepped up efforts to diversify the sources of their financial support by pursuing scientific research and closer ties to industry. According to Veysey, this era in the evolution of the American university was defined by the need to cultivate new sources of financial support from industry among other sources: "Financial support was constantly of greatest urgency for every academic establishment. Money had to be wooed, and when it was offered it had to be accepted. Rare was the college ... which turned down a vast gift because it had strings attached."[36]

Industrial support affected the universities in several ways. The rise of the new industries - the railroad, telegraph, iron and steel and later the electrical and chemical industries - brought a tremendous expansion in the need for technical talent. Initially, the demand was for undergraduate and masters' level engineers and applied science who could apply their knowledge to the problems of industry. However, there was some use of more advanced scientists by industry during the late nineteenth century. As Nelson and Wright note, in 1875, the Pennsylvania Railroad hired a Yale Ph.D. chemist to organize a laboratory for testing and analysis of materials provided by suppliers; and the company employed scientific research to develop improved lubricants for use in locomotives. Research conducted by a doctoral chemist at the Carnegie Steel Corporation led to the identification of higher quality ores that could be used to produce higher quality steel.[37]

Universities responded to the growing demand for technically trained personnel in industry by establishing new courses and programs in engineering.[38] MIT was founded as Boston Tech in 1865, and Stevens Institute of Technology was established in 1871. Yale University introduced mechanical engineering in 1862 and Columbia University opened its School of Mines in 1864. MIT introduced its first course in electrical engineering in 1882 and the electrical engineering department was established in 1902.[39] In 1916, MIT established the

School of Cooperative Engineering Practice, a cooperative program with industry, at the urging of Arthur D. Little, a graduate of the MIT program and with $300,000 from George Eastman. The program sent MIT students to work and industry and gave MIT engineers access to sophisticated industrial facilities.[40] In the 1920s, the electrical engineering department established a cooperative education program with GE, in which students divided their time between academic courses work and research at GE facilities in Lynn, Massachusetts and Schenectady, New York. GE initially hired one-half of theses students upon graduation, and the program was later joined by AT&T, Bell Labs, Western Electric and other companies. John Servos, an historian of science who has written extensively on MIT's relationship with industry, notes that at MIT it was felt that: "It was only through practice with industrial operations and techniques that the student could be prepared to handle the problems of scale arising from production." The number of engineering schools grew from just 6 in 1862 to 126 by 1917, and the number of engineering graduates grew from 100 in 1870 to 4,300 at the outbreak of world war I.[41] Still, during this time, American universities remained considerably behind German and other European universities in teaching and research of both a fundamental and applied nature in fields such as chemistry and physics.

The rise of science-based industries and the industrial R&D laboratory dramatically expanded the need for technical talent and provided a tremendous spur to research ties between the universities and industry. As numerous studies have noted, the basic model for the industrial

R&D laboratory was pioneered in the 1870s by Thomas Edison at his Menlo Park research laboratory.[42] The General Electric Research Laboratory was established in 1900 followed by DuPont, AT&T, Eastman Kodak, Westinghouse, General Motors and many others.[43] On the eve of the Great Depression, 115 of the 200 largest companies had established research laboratories; as many as 1,000 companies had some type of research facility.[44]

The universities became a source of talent for the new industrial R&D laboratories. Willis Whitney, a member of the chemistry department at MIT was hired as an early director of research at General Electric's largest manufacturing works in Schenectady, New York. Whitney late hired William Coolidge of MIT and Irving Langmuir, who later won a Nobel Prize in chemistry, from the Stevens Institute of Technology.[45] Whitney succeeded at developing a basic research focus at GE. Frank Jewett, director of the Bell Telephone Laboratories, received his Ph.D. at the University of Chicago. Charles Lee Reese moved to DuPont from his position as an adjunct faculty member in the department of chemistry at Johns Hopkins University.[46] In 1919, the Standard Oil Company of New Jersey hired three eminent academic scientists, Ira Remsen of Johns Hopkins, Warren Lewis of MIT, and Robert Millikan of Caltech to advise on its research activities and the establishment of its new research and development laboratory. In 1927, the company hired an assistant professor of chemical engineering at MIT, Robert Russell, to launch its new laboratory in synthetic fuels and subsequently recruited a staff composed mainly of MIT faculty and gradate students.[47] In 1937, Edward Conden left his tenured position at Princeton to establish a fundamental research program in high energy physics at ????? [ask David company].

The rise of foundations during the late 19th and early 20th centuries provided an early counterbalance to industrial funding. In 1889, Andrew Carnegie published *The Gospel of Wealth*, proclaiming the duty of wealthy industrialists to use their wealth to support universities and other institutions devoted to the advance of society; and over the course of the next few decades, Carnegie provided more than $20 million mainly to support the pursuit of pure science. In 1901, John D. Rockefeller founded the Rockefeller Institute of Medical Research to provide support to medical research at Johns Hopkins University and Harvard University, and twelve years later he established the Rockefeller Foundation[48] both to support research and as a vehicle for institutional and organizational change in the university. Foundation grants were sometimes used to underwrite the creation of new fields and departments, such as the electrical engineering program at MIT, the chemical engineering program at the University of Pittsburgh, the Stanford Food Research Institute, and the Johns Hopkins Medical Laboratory. As Nelson and Wright note, foundation funding allowed a number of universities and university programs to establish a certain distance from the more immediate demands of industry and to deepen and extend their capabilities in basic scientific research.[49] In short, foundation support went mainly to tended to counter-balance the more applied funding from industrial corporations. It also strengthened the hand of advocates of pure science, allowing recipients of these funds and some university departments to move away from reliance on industrial support.

Mellon Institute: A Precursor of University-Industry Research Centers

The formation of Mellon Institute in 1911 was an important precursor to contemporary university-industry research centers. Located adjacent to the University of Pittsburgh, it created both formal and informal links through which academic science could support the advance of industrial science and technology. Mellon Institute involved faculty and graduate students in research projects conducted for industrial firms established and financed by the Mellon family in the greater Pittsburgh region.[50]

The Mellon Institute forged direct ties between industrial and academic research.[51] It established a program of "industrial fellowships" in which companies would support graduate students who performed industrial research projects as part of their graduate studies. By 1936, annual fellowships reached more than $1 million per year. The Mellon Institute drew from the wide range of scientific and engineering expertise and the University of Pittsburgh, particularly in physical chemistry, biochemistry, and chemical engineering. It placed emphasis on the application of its expertise and talents to the applied and practical problems of local industry - and shaped its research program to support such demand. The core of its work primarily focussed on the materials, resource extractive and chemical industries that comprised the Pittsburgh industrial base, though Mellon Institute staff also worked on projects for food processing firms, lumber companies, and personal care product firms, and even local grocers.[52]

The Mellon Institute provided an early model for two types of university-industry research relationships. First, Mellon Institute stimulated the growth of industrial fellowship programs. In 1918, DuPont established a program of university fellowships to roughly 25 leading schools. As David Hounshell and John K. Smith note in their history of R&D at DuPont, the company gave a department one or more fellowships on an annual basis, and the department rotated the fellowships among the faculty who in turn granted them to their students. The DuPont fellowship program generated great interest on the part of universities and university faculty, and according to Hounshell and Smith, recipients frequently asked the company "for suggestions for research."[53] By 1928, 56 companies supported an estimated 95 fellowships nationwide, and by 1940 a national total of at least 721 awards were underwritten by 200 companies. In 1934, for example, General Motors, Westinghouse, Eli Lilly, the Carbide and Carbon Chemicals Corp., U.S. Industrial Alcohol Co., among others supported fellowships at Johns Hopkins University.[54]

Second and more important, the Mellon Institute provided an early model of a new organizational entity that combined university and industrial research. It thus stimulated the formation of other specialized institutions designed to link the universities to industry. Battelle Memorial Institute, for example, was founded in 1929 with an endowment of some $4 million to conduct materials research with close links to Ohio State University. The Armour Research Foundation of Chicago was established in 1936 by several faculty members of Chicago's Armour

Institute of Technology (later the Illinois Institute of Technology). The Institute of Paper Chemistry was organized in 1929 with ties to Wisconsin's Lawrence College and support coming from dues on member companies.[55] Later, the Stanford Research Park and the Research Triangle Park in North Carolina were established to link the universities and industry in a quest for broader economic and regional development.

Furthermore, the Mellon Institute prefigured tensions between the pursuit of fundamental science and the more applied orientation of industrial innovation. This in fact led to tensions between the Mellon Institute and the University of Pittsburgh. Some within the university openly questioned the academic value of work produced by Mellon fellows and wondered what, if anything, the university was getting out of that relationship. The relationship between the Institute and the university remained more or less arm's length, until they formally separated in ????.

Industrial Support for University Research

Industrial support for university research expanded significantly during the first decades of the twentieth century to meet the needs of increasingly science-based industry. A number of universities vigorously pursued industrial support as a vehicle to increase their research funding and pursue eminence, most notably MIT. As the following pages will show, while MIT used industrial support to fund its rise to scientific and technical eminence during the late 19th and early 20th century, industrial funding generated tensions within the Institute which echo those which remain at the core of university-industry research relationships to this day.

MIT's initial major foray into industrial research was the establishment of the Research Laboratory in Physical Chemistry in 1903 under the direction of Arthur A. Noyes. It followed with the Research Laboratory in Applied Chemistry under William H. Walker in 1908.[56] Both were semiautonomous units, and thus expected to cover expenses through research contracts with industry. The Research Laboratory in Applied Chemistry was the more successful of the two, at least in financial terms; and by 1921, it had generated roughly $200,000 in research contracts with industry.

MIT established its Division of Industrial Cooperation and Research in 1920, which evolved over the years into the university's Office of Sponsored Programs. MIT also set up its Technology Plan, the precursor to today's "industrial liaison" programs to secure corporate contributions to MIT's endowment in return for certain services to industry. Under the plan, corporations agreed to pay an annual retainer for five years, in return for access to MIT faculty and staff on technical matters, access to alumni and student files for recruiting, and use of the library. More than 180 companies pledged $1.2 million in the initial phase of these programs.[57]

MIT's responsiveness to industry needs generated considerable enthusiasm among and support from science-based businesses. Between 1911 and 1921, three of the nation's leading chemical industrialists, George Eastman, Pierre duPont and T. Coleman duPont, gave the institute more than $11 million in building and endowment support.[58] By the 1920s, MIT had used industrial support to pursue eminence through an applied version of academic science. Unlike the established, elite universities, its mission was defined by training engineers for industry and to providing direct services to industry as well. Initially, this strategy paid considerable financial dividends. Sponsored research grew from $100,000 in to $270,000 during the 1920s. Industrial support also contributed to the growth of MIT's endowment which climbed to $15 million in 1920 and $33 million by 1930 - making it the fifth largest university endowment in the country. Furthermore, through its joint efforts with industry, MIT developed a large and deep network of alumni engineers on the leading edge of industrial research and in positions of authority in industry. But, as the following section will show, industrial support eventually generated tensions which would affect the pursuit of eminence.

MIT research and talent also formed the basis for a number of early spin-off companies. As early as 1900, Walker formed a partnership with Arthur D. Little, who had studied chemistry at MIT in the 1880s, to provide industrial research on a consulting basis to firms. While Walker withdrew because of time demands in 1905, the firm, Arthur D. Little, Inc., became quite profitable. During the 1920s, Vannevar Bush developed mechanical and electrical calculators, forerunners of modern-day computers referred to as *differential analyzers*, which were sold in both the United States and Europe during the 1930s and 1940s.[59] Bush later helped to found the

American Appliance Company, which was later renamed the Raytheon Corporation.[60]

Other universities stepped up their own efforts to engage industry by establishing industrially-oriented laboratories and at times by redirecting their research toward more applied, industry-relevant endeavors. As early as 1890, the University of Wisconsin developed the "Babcock test" which provided a cheap and simple method of measuring the butterfat content of milk for use by the state's dairy industry. In 1916, the University of Washington organized a Bureau of Industrial Research to work on the problems of local industries. In 1917, the University of Oklahoma established its own Industrial Research Department to work on problems associated with the oil and gas industries. In 1918, the University of Chicago invited manufacturing companies to undertake industrial fellowships, promising to institute chemistry courses shaped to bring about closer cooperation between university scientists and industry. The University of Michigan established a department of engineering research in 1920 to do contract research for industry. The University of Illinois established a variety of specialized engineering programs to suit the needs of expanding industries. Purdue University developed specialized programs in railroad technology from locomotive repair to the design and maintenance of locomotive boilers. The University of Akron forged ties of its own with the local rubber industry, and developed specialized research capabilities in the processing of rubber. Both Carnegie Institute of Technology and the University of Pittsburgh developed teaching and research programs in metallurgy related to the growth and development of the steel industry in and around Pittsburgh. In an enormously successful program, the University of Minnesota's Mines Experiment Station conducted long-term research on the development of new methods and techniques for extracting lower-quality iron ores, a problem of considerable interest to mining companies whose activities had exhausted higher-quality ores. University-industry ties spread even into the social sciences, particularly economic and business research. The University of Pennsylvania established a department of industrial research in the Wharton School in 1919 to perform contract research on labor-management relations. The Harvard Economic Service was established to forecast business conditions for private subscribers.[61]

The rise of industrially-relevant research made control over intellectual property an increasingly important source of competitive industrial advantage. The ability to generate funds through control of intellectual property rights was not lost on the universities. In the teens and twenties, a number of universities established patent offices. Columbia University was among the first to establish an office to handle patents. MIT devised a complex system for splitting the patent rights for Van de Graaf's generator among itself, Princeton, and the National Research Council during this period.

The most significant university effort to patent its intellectual property was the Wisconsin Alumni Research Foundation or WARF, an administrative vehicle for protecting and promoting the intellectual property generated by faculty research. The impetus for WARF came in the 1920s, when a University of Wisconsin Professor, Harry Steenbock, published a paper on a irradiation process by which milk could be fortified with Vitamin D.[62] Both Steenbock and the university sought to patent his discovery and in 1924, WARF was created to manage the patenting process. Despite protests from the faculty, Steenbock received a patent on his discovery four years later. WARF then began to use the patent to recruit industrial firms to purchase the rights to the process, selling the license to Quaker Oats among others.[63] By 1931, seven years after its inception, WARF had accumulated over $1.6 million in assets. Thirty years later in 1961, WARF license fees had generated $60 million in revenues.

The Tension between Eminence and Industrial Support

Industrial funding of university research eventually generated tensions which affected and to some extent hindered the pursuit of eminence. Initially, these tensions took the form of faculty complaints and dissatisfaction over industrial influence over university work. During the first decades of the twentieth century, Thorstein Veblen issued a scathing indictment on the increasing industrial and business orientation of the American university, *Higher Learning in America*, with its subtitle: *A Memorandum on the Conduct of Universities by Business Men.* Over time, however, the use of industrial support as a strategy for pursuing eminence generated more deeper and more fundamental challenges. As industrial support for university research expanded and industrial influence over the scope and direction of that research grew, it became increasingly apparent that industrial funding rather than being a vehicle for obtaining eminence could at times become a threat to the very pursuit of that goal.

The tension between eminence and industrial support was reflected in a conflict that emerged between the two architects of MIT's early relationships with industry, Noyes and Walker. Noyes was the champion of basic science advocating "thorough training in the principles of fundamental science and in scientific method." Walker countered that it was more valuable and important to assist industry in developing innovations of more direct and immediate commercial benefit, noting that "it is a much smaller matter to both teach and learn pure science than it is to intelligently apply this science to the solution of problems as they arise in daily life." These tensions reverberated through the department and through the university as a whole. In the spring of 1919, Walker sent a memorandum to MIT President Richard Maclaurin threatening to resign if Noyes was not removed from the chemistry department. The MIT administration then asked Noyes to withdraw from the department and he soon left MIT for Caltech. The decision was astonishing given the fact that Noyes was one of the most renowned chemists in the country, held a top post with the National Research Council, and was a past acting president of MIT.

The situation at MIT presaged and mirrored that of the present day in many respects. As Geiger notes, MIT's experience raised two central issues which cut to the heart of evolving university-industry research ties. The first was whether industrial funding was compatible with basic scientific research or would it channel university research in a more applied direction while more fertile scientific fields of considerable long-run social and economic benefit were left unplowed. A persistent complaint among faculty at MIT and elsewhere during the 1920s was that industrial research was too concerned with "trivial" development problems, ignoring more important advances in fundamental science. On several occasions, Geiger points out, MIT faculty were prevented from publishing discoveries made under industrial support.

The second issue was whether or not private industry could provide the considerable level of support required to maintain high-quality university research. In the case of MIT, Geiger notes that while industrial support for research basically covered the costs of the research work, it yielded only modest spin-off benefits for the Institute. Some of the MIT laboratories, in particular the Research Laboratory in Applied Chemistry, in fact required infusions of institutional funds to sustain them. In addition, the temporary and short-term nature of industrial research done under contract meant that work loads fluctuated and staff had to be hired and let go to meet this changing demand. Even the centerpiece of MIT's relationships with industry, the Technology Plan, was in Geiger's view more a one-time windfall rather than a model for sustained cooperation: "When the institute attempted to sign subscription renewals after the initial five-year period, it found virtually no takers." Although MIT continued to receive contributions from industry for specific projects and programs, there was little core industrial support for ongoing activities at the university during the 1920s. The situation at MIT suggested that it was difficult, if not impossible, to use industry support to attain full stature as a scientifically-oriented research university. Industry support was not large enough to build broad-based academic credibility, and the research agenda was skewed heavily in the direction of applied research. As Geiger notes, "Loss of faculty in the basic sciences caused the Institute's prestige to drop in national comparisons. Troublesome conflicts between industrial and academic practices further alienated academically-inclined scientists."

Facing the tension between eminence and the pursuit of industrial support head on, MIT eventually moved away form its heavy focus on applied industrial research during the 1930s. Under the leadership of Karl Compton, the Institute began to bolster its capabilities in basic science, while instituting more effective administrative controls over industrial research. In Geiger's view, Compton "rescued" MIT from its overly applied orientation and short-term mentality and remade it as a modern research university. Compton, who had come from Princeton University, drew from the alternative model of the California Institute of Technology (Caltech), where a coalition of university leaders and local businesses parlayed foundation and corporate funds into longer term for "best science" and transformed the former Throop Institute of Technology into one of the top scientific universities in the world. In fact, the leaders of two of America's most technologically-advanced companies - Gerard Swope, president of General Electric and Frank Jewett of Bell Telephone - pressed for change, arguing that MIT had a responsibility to strengthen its basic science orientation, introduce more fundamental science into its engineering programs, and develop new, science-based teaching programs to rehabilitate its sagging academic reputation and turn out cutting-edge scientists and engineers for industry who could look beyond the practical concerns of the day. Under Compton, MIT developed policies to temper applied work in favor of a more basic scientific orientation, for example, it passed on routine industrial work to commercial laboratories, choosing to undertake only research of scientific import that required the special capabilities of its faculty.

University Initiative and Government Policy

While university initiative provided the immediate impulse for university-industry research realtionships during the early years of the 20th century, a series of government policies occurring during the latter half of that century provided the broader institutional context in which evolved into contemporary university-industry research centers. While it is safe to say that government policy government was at best marginal contributor to the early rise of university-industry research relationships, large-scale government funding of university research after World War II had a significant effect on these relationships. To some degree, massive government funding provided a new source of research support with which universities could pursue eminence. But, by the 1980s, changes in federal science policy, the creation of new tax advantages for industrial funding of academic research, and changes in intellectual property law which enabled universities to hold patents on government funded research provided a broad context which facilitated and even encouraged the formation of university-industry research centers.

Government support for research and academic science on a broad scale did not emerge until the Cold War era. Before then, government provided only limited support for academic research. Government support clearly added a major new player to the traditional relationships between universities and industry, adding complexity to the relationships among institutions involved in pursuing scientific advance. To a some extent, it can be said that government funding transformed the formerly bi-lateral relationships between universities and industry into a new set of tri-lateral relationships.

Furthermore, government funding alleviated the tension between industrial support and eminence, at least to some degree. Increased government support made universities less dependent upon industrial research support and enabled them to offset the more applied focus and restrictions associated with industrially-sponsored research. The rise of substantial government funding of university research in the Cold War era to some degree provided a mechanism for academic scientists to counterbalance industry support and gain a degree of independence to pursue more fundamental, curiosity driven research at least in some areas. Of course, a great deal of government funding, like industry funding, came with strings attached and was devoted to the pursuit of specific missions. Still, the rise of unconditional support for some fraction of academic research from the National Science Foundation and from several of the more mission-oriented agencies provided greater resources for the pursuit of fundamental science.

Before proceeding to our examination of the structure and nature of increased government support for university research and of its affects on academic science, it is important to note that in this book we are less interested in the structure and institutions of government policy per se, which have been well chronicled elsewhere, but rather focus on the ways those policies structure and condition the relationship between universities and industry.

There are several mechanisms through which government can affect university research. The first and most obvious is through direct spending. The second is through changes in tax policy, for example by establishing tax advantages for industrial sponsorship of academic research. The third is through intellectual property policy, for example by enabling universities to take patents on government funded research. The fourth is through regulatory policy which can work in two ways. On the one hand, relatively strict regulations can provide a direct stimulus to research and innovation in specific fields such as environmental health and safety. On the other hand, relatively lax regulations can stimulate research by providing a national regulatory climate which is more conducive to research than those of other countries, as in the case of the new biotechnologies. Government policy affects the nature of university research in several ways. The first class of effects are the direct and intended effects of government policies, such as the creation of new programs to stimulate research in certain areas or the use of tax breaks to stimulate industrial funding of academic research. The second class of effects are the indirect and unintended effects of government policies which, as their name implies, are considerably more difficult to anticipate, trace or even observe. Indirect and unintended effects of government policies can occur when government spending programs redirect attention and effort away from some areas or activities, or when perceptions of changes in government policy stimulate actions on the part of academic scientists or university officials. **WES AND LUCIEN CHECK, CLARIFY, AND ADD EXAMPLES OF UNINTENDED AND INDIRECT EFFECTS**

While a large and active government role in science policy is a product of the post world war II years, the main contours of the post war institutional relationships between universities and industry and government were outlined earlier, particularly during the period stretching between the two world wars. The earliest significant government interventions to support universities and university research date back to the Morrill Land Grant College Act of 1862 which provided federal funding in the form of land grants for colleges offering agricultural education and technical training. A number of the nation's premier research universities - the University of California, Cornell University, University of Michigan, University of Wisconsin, and even MIT - trace their origins in this land grant system. Later, the Hatch Act of 1887 provided each state with funding to establish an agricultural experiment station to conduct research on new farming technology and methods. These policies also helped to stimulate research in the universities, a good deal of which was of direct relevance to industry, through the vehicle of the agricultural experiment stations. The agricultural experiment station program at the University of Connecticut, for example, provided training in agricultural engineering as well as more direct technical assistance to the farm. The level of support was later doubled with the Adams of Act of 1906 and the establishment of the cooperative agricultural extension service in 1914.

Federal support for academic science initially grew during the mobilization effort for World War I, as the scientific and technical demands of armaments production brought about significant government funding for science during the mobilization effort for World War I. The National Research Council (NRC) oversaw this effort, forging close relationships between academic and industrial scientists. The NRC, according to Geiger, was "first and foremost a network for joining academic, industrial and government science."

The academic community began to organize and press for increased federal support during the Great Depression of the 1930s. In 1933, the Science Advisory Board was created as a temporary vehicle for providing science advice to the federal government and a mechanism for getting federal support for science written into New Deal legislation. However, the Board failed in its attempt to secure a $16 million appropriation for research projects in science and engineering under the National Industrial Recovery Act. The Board's Chairman, Karl Compton, later prepared a report, *A Program for Putting Science to Work for the National Welfare,* advocating temporary federal support for science and engineering. Efforts to obtain steady federal support for academic research through the Works Progress Administration and through increased appropriations to the National Bureau of Standards also largely failed. In 1938, a government report on the state of American science and technology, *Research: A National Resource*, made the case for greater federal support for academic science arguing that universities were the training ground for industrial researchers and engineers and accounted for nearly a third of all research scientists and a fifth of total research spending, concluding that "anything that the Government may do to stimulate and finance research in our universities and colleges will probably pay a high return on investment." Government support for research grew slowly during the Depression coming from a variety of federal programs, and by the end of the decade the federal government was providing roughly $100 million in annual support for university research. For the most part, government funding of science during the Depression was for projects with tightly defined public objectives and supported by mission-oriented agencies. In 1933, for example, roughly 40 percent of federal R&D went to agriculture and another 25 percent for national defense. The federal government supported Howard Aiken's work on the Mark I computer with IBM. Still, academic research and the universities weathered the storm of Depression better than most other institutions. As Geiger points out, at the end of the 1930s: "Essentially, conditions for investigators at research universities had never been better. Facilities, though largely erected in the preceding decade, were on the whole the finest in the world; teaching burdens, the perennial lament of American professors, had sunk to their lowest point, and assistance in teaching and research was available from abundant numbers of graduate assistants."

The mobilization effort for World War II and the subsequent Cold War set the contours for massively expanded federal support for academic science. In June 1940, the National Defense Research Committee was organized under the direction of Vannevar Bush and with an advisory board that included James Bryant Conant of Harvard University, Karl Compton of MIT, Frank Jewett of Bell Labs and Richard Tolman of Caltech to initiate, direct and fund research on scientific problems that were beyond the scope of existing military laboratories. By the end of 1940, the NDRC had initiated 132 contracts to 32 universities and 19 industrial corporations. Research areas included: microwave radar, night vision glasses, oxygen masks, fire-control equipment, rockets, antisubmarine warfare devices, high-explosives, chemical weapons, and improved battlefield equipment. In May 1941, the Office of Scientific Research and Development (OSRD) was established to coordinate the activities of the NDRC and the newly formed Committee on Medical Research. The OSRD ultimately spent some $450 million on weapons R&D and played the key role in many of the most important technological breakthroughs of the war effort. The OSRD also made a series of important organizational and administrative innovations that would come to imbue postwar science policy. The OSRD relied upon contracts with universities and the private sector for the performance of research that allowed full reimbursement of research costs. OSRD was a civilian agency and not under direct military control; members of the scientific community were called upon to make recommendations and to guide as well as to participate in OSRD research projects. Furthermore, the OSRD had a lean bureaucratic structure and favored decentralized decision-making by scientists themselves. As Harvey Brooks points out, scientists were allowed considerable freedom to pursue scientific and technical objectives during the war mobilization effort.

> Although in practice there was usually close cooperation with the military and with the defense industry, this often did not develop in specific areas unless the scientists were allowed the freedom and given the resources necessary to demonstrate to the military what was possible. As the U.S. entered the war, and urgency increased, the simultaneous pursuit of parallel technical paths to the same military problem came to be accepted as standard practice. This apparently costly strategy was based on a belief that the costs of R&D could be safely neglected in comparison to the losses that might ultimately be incurred by military failure. Military problems were formulated only the most general terms, a practice which came to be referred to as the "whole problem approach."

Federal R&D spending rose from $83.2 million in 1940 to a peak of $1.3 billion in 1945 (measured in constant 1930 dollars). Over the course of the war effort, MIT was awarded $117 million in R&D contracts, Caltech $83 million, and Harvard and Columbia about $30 million each.

The years immediately following World War II saw the institutionalization of a new set of relationships between the government, universities and industry, revolving around massively increased government funding for basic science. In July 1945, Vannevar Bush issued his historic report, *Science: The Endless Frontier* which argued that basic scientific research was the font of technological innovation and economic growth, and that the federal government bore a responsibility to encourage and support such research in the universities.

> New products, new industries and more jobs require continuous additions to knowledge of the laws of nature, and the application of that knowledge to practical purposes. Similarly our defense against aggression demands new knowledge so that we can develop new and improved weapons. ... Today, it is truer than ever that basic research is the pacemaker of technological progress. In the nineteenth century, Yankee mechanical ingenuity, building largely upon the basic discoveries of European scientists, could greatly advance the technical arm. Now the situation is different. *A nation which depends upon others for new basic scientific knowledge will be slow in its industrial progress and weak in its competitive position in world trade, regardless of its mechanical skill.*

Expanded federal support for academic research ushered in a new bi-lateral relationship between the universities and government, and enabled scientists more than ever before to pursue fundamental science unfettered by industry needs and applications. It was this relationship that has sometimes been dubbed the new *social contract* between science and the federal government which is often seen at the heart of the post-war science policy.

Federal support for R&D grew substantially in the post war era, stimulated initially by the Korean War and Sputnik, the expansion of government funding for health and medical science, and later by growing social needs and priorities. In 1946, Congress created the Atomic Energy Commission, the Office of Naval Research, and the National Institute of Mental Health. The National Science Foundation was established to fund basic science in 1950. According to David Mowery and Nathan Rosenberg, federal support for R&D grew from $4.7 billion (in constant 1972 dollars) in 1953 to $15.6 billion in 1963 and more than $18 billion by 1968, fluctuating between one-half and two-third of all R&D expenditures over that period. The National Science Foundation and National Institutes of Health provided substantial public funding for basic scientific research across a wide range of field and disciplines. In addition, agencies such as the Department of Defense and the Atomic Energy Commission provided even greater funding for applied research in fields of particular interest to them. Such massive government support for research made the United States the world's unquestioned leader in science, evident in the ability of U.S. universities to produce top-quality scientists, attract other leading scientists from around the world, and to win the lion's share of Nobel prizes. It was not until 1979, that the combined research and development spending of the four largest foreign industrial economies, Germany, France, the United Kingdom and Japan exceeded that of the United States.

The emergence of the new relationship among universities, industry, and government can be most clearly seen in the development of the computer. Government funding of computer technology began in the 1930s and was massively expanded during the war effort. After the war, government spending mainly by the Department of Defense led to major initiatives at several universities. Major advances in computer technology emerged from interactions between engineers and scientists at leading universities such as Harvard, MIT, and the University of Pennsylvania working closely with industrial researchers from Bell Labs, IBM and other companies supported by wartime and postwar government contracts. In a careful study of the origins of the computer industry, Kenneth Flamm points out that nearly every major development in the computer industry before 1960 was supported by the U.S. and to a lesser extent by the British government. Flamm estimates that in 1950 the U.S. government was spending between $15 and $20 million per year on computer related R&D. These funds helped to lubricate the relationship between academic and industrial researchers. The Mark I computer, begun in the pre-war period, was a result of collaboration between Harvard and IBM researchers. The ENIAC developed by Eckert and Mauchly of the University of Pennsylvania was initially supported by the OSRD. Subsequent generations of computers, including the UNIVAC, were produced by a spinoff company, the Eckert Mauchly Corporation. Engineering Research

Associates (ERA), a company founded during the World War II by William Norris, who would later go on to establish Control Data Corporation, forged close ties to MIT to produce cryptological devices for the Navy, magnetic drum memories, and the nation's first successful digital computers, controlling some 80 percent of the computer market in 1952. These efforts were stimulated not only by direct government support for research, but by the large and expanding government market for computer technology. By the 1960s, the use of government funds to prove the feasibility of computer technology helped to establish a vibrant and massively expanding commercial market for computers.

The rise of government support for fundamental science in turn gave rise to considerable discussion and debate over the efficacy of pursuing research designed to advance fundamental science versus research of a more applied and relevant nature. This debate focussed both on the most efficient path to achieving scientific and technical progress and on the implications of the different styles of research, in particular research that was closely linked to institutional missions, on the underlying norms of open science which lie at the core of academic research. Here, it is useful to point out that while the Bush report, *Science: The Endless Frontier*, is often interpreted as making a strong case for federal support of basic research, in reality, Bush and other leading scientists of the period appear to have had a more nuanced view of the relationship between pure and applied science, stemming in large measure from their war time experiences. The emphasis on the interaction and complementarily between these two forms of science is clearly articulated in the 1949 report of a committee chaired by Bush and including other eminent scientists including John von Neuman, Zay Zefferies and others to Harvard University President James Conant on the use of the Gordon McKay bequest to establish applied science and engineering at Harvard University.

> The borderline between the engineer and the applied scientist is becoming dimmed. It has never been clear cut. An applied scientist is one who renders science useful, an engineer is one who utilizes science in an economic manner for man's benefit. The difference has in the past been mainly that the former starts as scientist and seeks to apply, while the latter begins with the appreciation of a human need and searches out the science by which it can be met. Yet even this difference is becoming modified. Engineers, those who are really at the forefront of advance, are becoming more entitled to be recognized as scientists in their own right. Applied scientists, under the pressure of war and its aftermath, have often been accomplished engineers as well. ... A science, such as physics or chemistry or mathematics, is not the sum of two discrete parts, one pure and the other applied. It is an organic whole, with complex interrelationships throughout. There should be no divorcing of applied science from its parent systems. ... Certainly, whatever the organization, there should be a community of interest, a vigorous interchange of ideas and students, between the department of mathematics and the applied mathematicians of whatever stamp who are operating directly in the field of

applied science and engineering, and this same principle should apply elsewhere.

As Brooks notes, the postwar emphasis on basic research as a distinct form of scientific activity evolved mainly from the fear, often justified by experience, that a Gresham's law tended to operate when basic and applied research were made to compete for politically allocated resources. Basically, the fear was that short term goals with clear missions and objectives would drive out important longer term efforts, since the former could be made more palatable in popular and political terms.

University-Industry Relations in the Cold War Era

Government support of science in the Cold War era was concentrated in two main areas: support for military research mainly in nuclear, electronics and aerospace technologies and the health and biomedical technologies. Historians of Cold War science and technology such as David Noble, Daniel Kevles, Paul Forman and Stuart Leslie have noted the increased role of military funding on academic science in physics, computer science and related fields during the cold war era, suggesting the rise of a "miliary-industrial-academic complex." They further suggest that military funding of academic research skewed the content and nature of scientific research in the United States toward military-defined research objectives, and in doing so, diverted both scientific resources and talent way from both the pursuit of more fundamental science and science to devoted to solving pressing domestic social and economic needs. Paul Forman has argued that the purpose and character of physics research was altered both by the size and source of funds during the Cold War.

Their work has given rise to a considerable debate over the role of function of cold war science, sometimes referred to as the "distortionist debate," referring to the hypothesis that military funding distorted scientific priorities. In a critique of the distortionist hypothesis, Geiger has argued that scientific development was not distorted but largely complemented by military research. A recent review of this debate by leading historians and social scientists working in the field of science and technology studies suggests that the issues of whether or not Cold War military funding distorted the production of scientific knowledge, and if so, to what degree, remain open questions.

Here, it is also important to note that although military support provided the preponderance of federal research funding during the 1950s, it became a minority supporter of academic research, except in engineering, by the 1960s due mainly to the explosive growth of funding for medical-related research. Only in the period from 1947 to 1960 was the Defense Department the major player in academic research. During the early 1950s, for example, the military and the Atomic Energy Commission provided roughly 70 percent of external research support to universities. At no time after that did the Defense Department account for more than 15 percent of support for academic research in the universities proper as opposed to national laboratories connected to universities. In addition, the influence of Defense Department support on the research agenda was mainly confined to the field of aerospace and electrical engineering. By the end of the 1960s, military support for academic research had dropped to below 10 percent, before growing to more than 15 percent during the Carter-Reagan defense build-up of the late 1970s and 1980s. Military funding conditioned a new set of bi-lateral relationships between the universities and the federal government, which manifested itself mainly in significant federal funding for defense contract research centers and laboratories operated by the universities.

Many commentators have suggested that national security considerations and the rise of classified research challenged the traditional norm of free public disclosure of research discoveries and open science. These issues were certainly a source of considerable debate in American universities. At least one university took a firm position on the issue of classified research. Immediately after world war II, Harvard University prohibited its faculty from engaging in classified research as part of their formal university duties and forbid the acceptance of grants to conduct classified research by the university, although Harvard faculty were allowed to work on classified military projects as part of their independent consulting and not using university facilities. Furthermore, as Harvey Brooks points out, the great bulk of classified military research took place in government laboratories affiliated with universities or other "buffer institutions" which were somewhat separate from the university proper.

> Despite heavy recruitment of Ph.D. engineers into defense-related programs, however, engineering departments themselves were not heavily involved in development work directly related to specific weapons systems or other defense missions. The more strongly mission-oriented defense R&D was conducted largely in separate federal contract research centers often operated by universities, but quite separated from regular academic programs or graduate student research leading to an advanced degree.

Brooks further notes that even though these contract research centers were restricted from communicating their discoveries with the outside world, there was a free flow of information within them. As Chapter 5 will show, this is to some extent different from a new class of information restrictions which has grown up in current day university-industry research centers where in some cases professors in the same center or department are prohibited from sharing the findings of their industry-supported research with one another.

The major federal role in academic research came not in the form of defense funding, however, but rather through the explosive growth in government support for health and biomedical research in the past three or four decades. Beginning in the late 1950s, the National Institutes of Health became the largest sponsor of academic research by far contributing more than 40 percent of funds for university research. In fact, given the size and structure of NIH funding, it may be more accurate to speak of the development of a "biomedical-academic-industrial complex" with the dramatic rise in research funding from the NIH and the close ties of that funding to both universities and major biomedical corporations. NIH funding also appears to have had a significant effect on the structure of the academic research agenda in biomedical science and its clinical applications, consistent with the fact that the total biomedical complex represents nearly 15 percent of GNP whereas the defense complex never exceeded about 6 percent of GNP after 1960.

WES and LUCIEN TAKE A CLOSE LOOK AT THIS NEXT PARAGRAPH

But, the particular issue of relevance to this book is as follows: What, if any, role did government funding play in altering the relationship between the universities and industry? A number of commentators have argued that massively expanded government funding for science in the Cold War had the effect of supplanting industrial support for academic research. Such explanations are only partly correct. Industrial funding of university research did decline from an 8.1 percent share in 1955 to 6 percent in 1960 before trailing off to 2.5 percent by 1970. This was more the result of the enormous increase in new forms of government research support, mainly from the NIH, than a decline in industry support of academic research. In fact, as large technologically-advanced firms developed their own cutting-edge research programs, they looked to universities for more generic and theoretical knowledge that could supplement and enrich their own internal R&D efforts. With plentiful sources of funds from the federal government, the universities accepted and even encouraged this division of labor in research work. Government support did not necessarily supplant ties between the universities and industry. In many fields of technology, it actually encouraged and facilitated such ties, creating new tri-lateral relationships, as was noted above in the case of early computer development. Such ties were also evident, as the next sections will show, in relationship of MIT to the growth of high-technology industry in the Route 128 complex around Boston, the role played by Stanford University in Silicon Valley high technology, and the close interactions between universities and industries in the rise of the new biotechnologies. It is to these issues that we now turn.

The University, Venture Capital and High-Technology Industry

The post-war era saw another twist in the evolution of ties between university and industry - the rise of a new model of entrepreneurial high-technology around MIT and Stanford University. MIT was in many respects the pioneer of this new model of university research, venture capital and high-technology enterprise. In 1945, three scientists in the MIT Radiation Laboratory founded Edgerton, Germeshausen and Grier, Inc., or EG&G, Inc., to work on government contracts that were "too highly" classified for MIT. The Research Laboratory in Electronics gave rise to fourteen companies in just its first two decades of operation, nearly all with close ties to and support from the military.

MIT also played a hand in the first technology-oriented venture capital fund with close ties to university research - American Research and Development Corporation (ARD) established in 1946 to supply venture capital to technology-intensive enterprises. Three of ARD's initial investments were MIT spin-offs, Tracerlab and the High Voltage Engineering Co, and Digital Equipment Corporation, founded in 1957 by Kenneth Olsen and Harlan Anderson of MIT's Lincoln Laboratories. ARD's success stimulated the formation of dozens of additional venture capital funds, which in turn provided a source of capital for more university-based technology companies trading their capital for an equity stake in newly created enterprises. Research by Edward Roberts found that more than 100 high-technology companies founded during the postwar period could trace their origins to faculty and staff during the post-war era, including Lotus Development, one of the earliest, successful personal computer software companies. A 1990 report by the Bank of Boston found that individuals related to MIT had generated 636 new businesses in Massachusetts generating $40 billion in sales, including 57 new software companies and 20 new biotechnology start-up companies in the period 1980 to 1989. By the early 1980s, the ability of academic researchers to attract venture capital and launch new enterprises was seen by some as an alternative source of research support. When two MIT faculty members, Gregory Yudek and John Vander Sande, visited the university's development office in the early 1980s for advice on how to generate research support, they were directed not to federal funding agencies but rather to a local venture capitalist, with close ties to MIT, George McKinney of ARD, and embarked upon the creation of a new start-up company, American

Superconductor Corporation, to further their research as well as to commercialize its products.

Stanford University provides another example of this model of academic entrepreneurship. The words of Dean Frederick Terman, the goal was to build a "community of technical scholars ... composed of industries using highly sophisticated technologies, together with a strong university that is sensitive to the creative abilities of the surrounding industry." Government provided the research funds which enabled the university to build its research base. Those fund led in turn to product orders and procurement which created the markets for new companies. The companies in turn were established by Stanford University graduate students, acting on the advice and with the assistance of key faculty and administrators. The companies provided new sources of revenues for the university, and ultimately a base of tenants for its newly created Industrial Park. Terman was instrumental in convincing two of his graduate students, William Hewlett and David Packard, to form Hewlett-Packard in 1937. Terman also gave Charles Litton of Litton Engineering laboratories his start as a research associate during the 1930s; and Terman was later instrumental in securing the wartime and postwar contracts, which allowed Litton to grow into a multi-million dollar company. He did much the same for Varian Associates, which emerged from government-funded research projects at Stanford University on the klystron, a flexible microwave receiver and transmitter.

Terman returned to Stanford University as dean of engineering in 1946, and Stanford rapidly increased its performance of government funded research. Terman used these funds to bankroll his highly successful program of building "steeples of excellence" - programs of research excellence in selected important fields. Terman established a series of laboratories, the Electronics Research Laboratory and the Applied Electronics Laboratory, which he later combined into Stanford Electronics Laboratories to attract these funds. Terman also established the Stanford Industrial Park, to house spin-off companies from the university and to attract the research and technical facilities of world class companies such as GE, Westinghouse, Eastman Kodak, IBM, Raytheon, Lockheed Aerospace, ITT, Sylvania, and the Xerox Palo Alto Research Center (PARC) in 1970. Terman also helped convince William Shockley to establish Shockley Semiconductor in the industrial park in 1955. This led in turn to the formation of Fairchild Semiconductor two years later which would later spark the growth of Silicon Valley as the center for the modern microelectronics industry. The Stanford Research Institute was later established to conduct more applied research for defense purposes and for industry. Terman also developed lucrative educational arrangements with local high-technology industry, including the requirement that firms pay double tuition for courses taken by their employees. The Stanford Honors Cooperative program encouraged engineers at local electronics companies to enroll in graduate courses directly or through a televised instructional network that broadcast these courses in company classrooms.

The success of Stanford and MIT sparked a wave of imitation. Beginning in the 1960s and continuing through the 1970s and 1980s, university and government officials across the

United States attempted to recreate the model of Stanford in Silicon Valley or MIT in the Route 128 area surrounding Boston. The model itself was simple in theory, but almost impossible to replicate in practice. In an era of rapid technological change, the university should play a more central role in the process of technological change and regional development. New directions in federal and state policy reinforced this view; government support should encourage closer university-industry relations to promote technological, economic, and regional progress. The mounting economic problems experienced in the 1970s and early 1980s, particularly in older manufacturing regions like the industrial midwest, only accelerated this movement, as region after region developed strategies to become the "next Silicon Valley."

Science as Industry: The Biotechnology Revolution

The rise of the new biotechnologies during the 1970s and 1980s was of central importance to the resurgence of formal university-industry research relationships, as it brought to the fore a new industry that was closely tied to academic science. The industry itself was born from Nobel-prize winning academic science, the Boyer-Crick patent on DNA and subsequent work by Boyer and Cohen on genetic splicing. Knowledge regarding recombinant DNA and genetic engineering was almost exclusively the province of academic scientists. As Martin Kenney has noted, while many large companies temporarily ignored the commercial implications of these developments, venture capitalists and academic scientists quickly jumped into the breech. In 1976, Robert Swanson a venture capitalist founded Genentech by enlisting the Nobel prize winning scientist, Herbert Boyer of the University of California of San Francisco to develop the research strategy and assemble the research team, which he did without ever leaving his academic post. Between 1980 and 1984, more than 200 new biotechnology firms were formed - many, if not most, originating in the laboratories of academic scientists.

Universities recognized the value of this new technology in generating both industrial support and in the pursuit of eminence. In 1974, Harvard University entered into $23 million agreement with Monsanto to conduct cell research at its medical school, agreeing to transfer the patent rights from the university to the company, among other things this contradicted a longstanding policy of dedicating health-related patents to the public. In April 1981, the German pharmaceutical company, Hoechst A.G., provided a $70 million grant to Massachusetts General Hospital to establish a genetics department in conjunction with Harvard Medical School. In May of that year, Harvard Medical School announced a third agreement - a $6 million five-year research arrangement with DuPont, giving DuPont exclusive rights to the resulting patents. In September 1981, Washington University in St. Louis entered into a $3.9 million research agreement with Mallinckrodt, Inc., a producer of chemicals, to conduct research on hybridomas, a technique for producing antibodies and another biological materials. Between 1981 and 1984, U.S. universities established eleven major multimillion dollar research relationships with the biotechnology industry.

The rise of the new biotechnologies rekindled the nearly century old tension between industrial support and the pursuit of eminence. To some extent, however, this tension was muted by the close ties between academic science and industrial application in this field. Nonetheless, tensions and conflicts did emerge. For one, professors sat at the center of many biotechnology companies, not only as consultants and advisors, but as owners with significant equity stakes in these enterprise. Furthermore, commercial considerations in this field were seen to impede the free and open disclosure of scientific findings. For perhaps the first time, scientists in the same department (with industrial funding) were withholding (commercially-relevant) discoveries from one another. All of this was further complicated by the fact that many of these scientists were also key members of scientific committees and peer review networks that were responsible for the allocation of millions of dollars in federal research funds. **WES/ LUCIEN NEED A SUMMARY SENTENCE OR TWO HERE ON IMPLICATIONS. MAY NEED TO HIGHLIGHT BLUMENTHALS' RESULTS, THOUGH WE DO THAT IN OTHER PLACES**

The Resurgence of University-Industry Research Relations

University-industry research relationships witnessed considerable expansion. As Chapter 1 has noted, industrial support for university research increased more than six times in real terms from the 1970s to the 1990s. Universities doubled their share of the nation's total R&D

effort over this period. A large fraction of university-industry research relationships took the form of joint research centers supported by government as well as industrial funds. But, the resurgence in relationships between universities and industry went beyond joint research centers. A number of universities developed programs to finance spin-off companies, by establishing their own venture capital funds or cooperating closely with venture capitalists and by investing university endowments funds in start-up enterprises. In an extraordinary example, Boston University invested a considerable share of its endowment in Seragen, a biotechnology company. Carnegie Mellon University invested in Next, Stephen Jobs' post-Apple start-up company, and formed the Enterprise Corporation in conjunction with the University of Pittsburgh to provide advice and assistance to new start-up companies. Harvard University formed its own limited partnership to commercialize discoveries made by its medical school. Johns Hopkins University created a similar structure, the Dome Corporation. MIT worked closely with local venture capitalists to encourage the formation of spin-off companies by its faculty and even acquired direct equity positions in new startup enterprises in return for licenses to patents. Case Western Reserve University established a non-profit subsidiary, University Technology Inc., to oversee various technology transfer and commercialization activities. A growing number of universities established research parks to attract private enterprise to the university campus, forge closer links to industry, and encourage the commercialization of university science and technology. By the mid 1980s, some 35 universities had established research parks, and another 40 had research parks under development.

These efforts and activities were ostensibly motivated by concerns over declining American technological and industrial performance. As a large number of reports have recounted, America's unquestioned economic dominance in the world economy declined somewhat during the 1970s and 1980s, as a number of foreign nations experienced high rates of productivity increase and economic growth. The sagging performance of a number of U.S. industrial sectors and mounting trade deficits in key manufacturing industries prompted the call for policy strategies to restore the so-called "competitiveness" of the U.S. economy. Increasing emphasis was placed upon technological innovation which remained a U.S. strength and which appeared to provide a key factor in the restoration of economic growth. A 1982 report by Business Higher Education Forum entitled *America's Competitive Challenge* was one of many of a genre which argued that university research was a indispensable asset in the quest for industrial competitiveness.

Government policies played three important roles in conditioning the resurgence of university-industry research relationships in general, and university-industry research centers in particular. First, the federal government launched a series of initiatives to directly stimulate university-industry research centers. In the early 1970s, National Science Foundation (NSF) provided funding under its RANN program for cooperative research centers at three universities: the Processing Research Institute at Carnegie Mellon, the Polymer Processing Program at MIT, and a applied research institute on the furniture industry at North Carolina State University. According to Smith and Karlesky, the Processing Research Institute generated $800,000 in industrial support from 26 firms and industrial associations including DuPont, Exxon, Xerox, Alcoa and Ford and an additional $500,000 in matching support from the NSF. The NSF also provided $3 million to established three "innovation centers" at Carnegie Mellon, MIT and the University of Oregon to promote university-industry interaction and technology transfer. In 1975, the State of Michigan established the Michigan Energy and Resource and Research Association, a consortium of large companies such as Dow Chemical and Detroit Edison, state universities, and state government agencies. Carnegie Mellon's Robotics Institute was started with support form Westinghouse, DARPA, the Office of Naval Research, and the NSF. In 1978, the National Science Foundation expanded its effort to stimulate university-industry research centers with the creation of the University-Industry Cooperative Research Centers program. The following year saw the release of a major federal report on industrial innovation, which identified university research as an under-utilized resource and called for increased support for joint university-industry research initiatives to enhance the development of new commercial technology by American industry.

During the mid-1980s, the National Science Foundation, under Erich Bloch, its first director from industry, made university-industry research centers a cornerstone of its mission, establishing the Engineering Research Centers program in 1984 and the Science and Technology

Centers program in 1987. These programs were designed to establish new research centers at universities with close ties to industry; to ensure this, they required participating universities to obtain matching support from industry. State governments developed programs of their own to stimulate university-industry research relationships, most notably Pennsylvania's Ben Franklin Partnership, Ohio's Thomas Edison program, the New York Science and Technology Foundation, the Michigan Strategic Fund, and New Jersey's Advanced Technology Centers. By 1990, 24 states had established technology programs that provided research grants for universities to form partnerships with industry, and 26 states had established programs that funded university-industry research centers to conduct cooperative research with industry. A 1988 study estimated that some 43 states had initiated such programs with expenditures totalling $550 million.

Second, the government established considerable tax advantages for industry sponsorship of academic research. The Tax Reform Act of 1980 enabled industry to claim any sponsorship of academic research as a tax write-off, including research of direct industrial relevance.

Third, changes in intellectual property policy created an additional stimulus for university-industry research relationships. The Patent and Trademark Act of 1980 allowed universities to claim the patent rights for innovations made with federal funds. The Uniform Patent Act of 1983 expanded the prerogative to disperse patent rights from federally-funded research, including a mandate that a share of the royalties derived from such patents be allocated to the original inventor. Other universities established new patent offices and offices of technology licensing not only to capitalize on existing patents but to search for potentially patentable innovations and "educate" university faculty members on the commercial potential of their research. Between 1980 and 1990, the number of patents awarded to American universities increased by more than 100 percent over the previous decade, though revenues generated from those patents were not particularly large.

The rapid growth and expansion of university-industry research relationships during the 1980s and 1990s rekindled the tension between eminence and industrial support which had been dormant for much of the post World War II period. While much of the discussion and writing on university-industry research relationships during the early to mid 1980s tended to view such relationships in a positive light, by the late 1980s and 1990s, questions were being raised about the efficacy of such relationships. Paul David and Parth Dasgupta questioned university-industry relationships ..... Henry Etzkowitz and others to conclude that the core mission of the university is being broadened from teaching and research to include direct and active participation in the development and commercialization of technology and in the broader process of economic development. But, as we have seen, a strong entrepreneurial current runs through the broader evolution of university-industry relations over the course of the entire past century. American universities have acted strategically over the course of the past century and before, maneuvering the shifting currents of government funding and changing industrial needs and priorities to build and maintain their own programs and capacities.

This paragraph should provide transition and contrast for following chapters where we will examine UIRCs and their role in eminence/industrial support directly. First look at their scope, then impact on performance, then back to eminence and enterprise.

SUMMARY POINTS

Wes/ Lucien let's agree on these summary points and I will write them up

UIRCs are the product of a century long organizational evolution - just one moment in that ongoing evolutionary process.

- university initiative -immediate impulse
- university initiative occurs and evolves in the context of government policies
- government policies are more than just NSF spending - tax and intellectual property policy are also important in establishing the terrain on which UIRCS are established.
- Government policies have intended and unintended consequences
- UIRCS reignites the tension between eminence and industrial support, and now bring government policy into that tension

Chapter 3

University-Industry Research Centers in the 1990s

> Even successful ideas born in university laboratories can take too long to be transformed into useful commercial products. One of the most promising new responses to this dilemma is the recent emergence of "centers of innovation" at many U.S. universities. These are industry-university consortia organized to create new knowledge and to transfer it more effectively from universities and colleges to the commercial environment. These centers take many different forms and perform many different tasks. But one thing they have in common is their potential to revolutionize not only education but the economy as well. The rapid evolution of these centers has so far proceeded largely unnoticed by the public and by the architects of industrial policy. But it would be a mistake to ignore their potential to accelerate innovation and to prepare Americans for a restructured, technology intensive economy (*The Innovators*, 1984).

The debate over closer relationships between the universities and industry has certainly grown more intensive over the past decade. Congressional hearings have probed the issue. Government agencies, the scientific associations, and numerous task forces composed of leading business, university and government officials have issued their reports. The issues were, and are, many and varied; some of them old, some of them new: the ability of universities to control and to distribute intellectual property, the role of academic scientists in spinoff companies, the perception of increasing foreign sponsorship and control over research at American universities, and all of this occurring in the context of growing federal investment in and support of academic science. Yet, as is so often the case, this debate has taken place in the virtual absence of systematic evidence and actual data from which to accurately assess the scope, activities and implications of university-industry research relationships.

This chapter endeavors to fill that gap. In doing so, it moves our discussion and analysis from a focus on history and institutional evolution to an empirical examination of university-industry research relationships in the here and now. We focus on what is arguably the most extensive form of interaction between universities and industry--jointly funded university-industry research centers. This chapter provides new and unique data on the magnitude and extent of these centers based upon our recent, national survey of their activities. The issues are many and varied. How extensive are university-industry research centers? How much is spent on them? How many universities participate? Who has provided the impetus behind their formation--industry, government, the university? What are their major sources of funds? What exactly do these centers do? In what industries and fields are these centers concentrated? This chapter addresses each of these questions.

Scope and Magnitude of University-Industry Research Centers

Both the number of university-industry research centers and the magnitude of R&D effort associated with them are quite large. According to estimates derived from our survey results, there were 1,056 university-industry research centers in existence at more than 200 university and college campuses as of 1990. These centers spent a total of $4.12 billion on research and related activities, and, of that, $2.89 billion was devoted exclusively to research and development.

It is useful to clarify the procedures we used to estimate these expenditures. The total expenditures for the 410 centers that responded to this question on the survey was $1.60 billion. These centers represent 38.8 percent of the population of 1,056 centers. Assuming that the expenditures for these responding centers are representative of the broader population, this implies total expenditures of $4.12 billion. We believe that this estimate may be conservative since our sample did not include all the universities that may house university-industry research centers; only 92.4 percent of universities responded to the first stage survey (see Appendix A).

University-industry research centers make a very important contribution to this nation's academic research effort, providing $2.89 billion for this purpose alone. To put this in context, consider that the total R&D expenditures of the National Science Foundation were $1.73 billion, that total federal spending on academic R&D at universities and colleges was $9.64 billion, and that total national spending for academic science and engineering R&D at universities and colleges in 1990 was $16.3 billion in 1990. In other words, the research and development expenditures by university-industry research centers represented 17.7 percent of total spending for academic R&D in 1990. Our estimate for R&D spending is based upon the fact that over 70 percent of the effort of these centers is devoted to R&D.

University-industry research centers have grown rapidly in the past decade. More than half of all centers in existence today were established during the 1980s. As Figure 3-1 shows, 284 centers or about 58 percent of the centers in our sample were established between 1980 and 1989, with the five year period, 1984-1989, being the most active. These data confirm a main finding of the historical analysis presented in the previous chapter. Despite the recent increase in their number, university-industry research centers are not a new type of institution. Of the centers in our sample, 16 were founded before 1900 and 59 were established before 1950.

The average university-industry research center is fairly large, having a budget of $4.05 million in 1990, including in-kind contributions. But, this average figure partly reflects the ffects of a handful of particularly large centers, as the median budget size was considerably less--$1.40 million. As Table 3-1 shows, roughly two-thirds of centers had expenditures between $100,000 and $2.5 million, 14.9 percent had expenditures between $2.5 and $5 million, 9.8 percent were in the $5-$10 million range; and 8.5 percent had expenditures between $10 and $55 million. Furthermore, a relatively small number of centers account for a disproportionate share of total expenditures. Just the 42 centers with the top 10 percent of expenditures accounted for 54 percent of total expenditures. And, the 21 centers with the top 5 percent expenditure accounted for 39 percent of total expenditures. Interestingly, centers engaged in agriculture-related research represent almost half of the top 5 percent (9 of 21) in terms of spending. Although only 20 percent (103) of centers in our sample listed agriculture as one of their areas of activity, spending by these 89 agriculture-related centers account for 35 percent of total expenditures. Most of these centers indicated that they conduct manufacturing-related R&D as well. The next largest centers in terms of spending were in the field of computing, specifically supercomputing.

[Table 3-1 about here]

A considerable number of university faculty, researchers and students are involved in, or at the very least exposed to, university-industry research centers. Approximately 19,000 university faculty members and 29,600 doctoral-level researchers (including faculty, research scientists and postdoctoral fellows) were involved in these centers nationwide, representing 21.8 percent of the 136,000 doctoral-level scientists and engineers involved in academic R&D in 1989. Approximately 27,000 graduate students were exposed to university-industry research centers. This corresponds to roughly 9.3 percent of the almost 300,000 (288,981) full-time graduate students enrolled in science and engineering programs in 1989. Table 3-2 reports the numbers of faculty, research scientists, postdoctoral fellows, technical and support staff, graduate students and undergraduates employed by university-industry research centers. Each center involved an average of 66.6 people and a median number of 23 employees including faculty, research scientists, students and staff. This included an average of 11.5 faculty, 6.5 research scientists, 3.1 postdoctoral fellows, 15.9 graduate students, 9.0 undergraduates and 20.6 staff. The median numbers for each category were substantially smaller, with a median of two faculty, three graduate students, four staff, one research scientist, one postdoctoral fellow and no undergraduates. The average number of R&D projects per center was 35.4, and the median was 15.

[Table 3-2 about here]

Industry Participation

Industry involvement in university-industry centers is widespread, and it appears to be growing (see Table 3-3). While our data do not allow us to identify how many companies nationwide participate, an average of 17.6 companies participated in each center in 1990--the median being six. This represented a modest increase from 1986, when the average was 11.4 and the median was three. Two-thirds of centers had relationships with 10 or fewer companies as of 1990. Twenty-eight percent had relationships with between 10 and 50 companies. Slightly more than 5 percent (5.5 percent) had relationships with more than 50 companies.

[Table 3-3 about here]

Foreign Companies

A contentious debate has recently emerged over the role of foreign funding of research at

American universities. On the one side are those that contend that foreign companies are gaining increased access to scientific and technical advances generated in U.S. universities, advances that have paid for mainly by the American public. On the other are those who argue that as open institutions with a mission to contribute to knowledge, universities should not exclude foreign sources of funding, provided that such support, as with any research funding, helps to advance academic science and is in sync with the norms that govern university research. Despite all of the controversy, this debate has thus far taken place in a vacuum, as reliable data on the research contributions of foreign firms is scant.

The most recent examinations of foreign funding of university research come from two studies prepared by the U.S. General Accounting Office (GAO) in the late 1980s. These studies indicate that the share of foreign funding of American university research is quite small. The GAO studies estimated that foreign institutions sponsored approximately $75 million in research at American universities or about 1 percent of total university research and development in fiscal 1986, with the leading contributor being firms from Japan, the United Kingdom and Germany. According to the GAO studies, a little more than a third of foreign research funding came from industry, with two-thirds coming from government and non-profit organizations. Furthermore, foreign research funding provided more than 2 percent of total research support at just 4 of the top 20 U.S. research universities, and between 1 and 2 percent of total support at eight more. [WES: WE COULD USE PROCTOR REID TABLE ON FOREIGN RESEARCH FUNDING

AT UNIVERSITIES, P. 11, HERE]

Our survey provides the first reliable and systematic source of data on foreign company participation in university-industry research centers. Overall, our data indicate that foreign companies represent roughly 12 percent (11.7 percent) of all industrial participants in university-industry research centers. On average, the centers in our sample had 1.7 foreign company participants per center out of an average total of 17 industrial firms. As Table 3-4 shows, the number of foreign company participants varied considerably by the specific field of technology that a center works in. Foreign firms comprised roughly 15 percent of all industrial participants in the biotechnology, biomedical, pharmaceutical and chemical fields. Foreign firms comprised more than 10 percent of industrial participants in the fields of advanced materials, scientific instruments and agriculture. The transportation sector had far and way the largest average number of foreign participants, with 3.6 foreign companies per center, followed by chemical, biotechnology, computer hardware, robotics, and agriculture which each averaged more than 2 foreign participants per center.

[Table 3-4 about here]

Geographic Distribution

The past several years have seen an interesting debate over the geographic distribution of academic research. Traditionally, support for academic research has been highly concentrated in a relatively small number of universities which have top reputations and have attracted the best scientists and engineers. In a recent report for the Andrew Mellon Foundation, Irwin Feller and Roger Geiger of Pennsylvania State University provide evidence that the postwar era has been characterized by the growing "dispersion" of academic research to much wider group of universities. They suggest that such dispersion has been a principal goal of U.S. science policy and of other research funders such as the foundations. Feller and Geiger also point out that in the 1980s and 1990s the debate over the dispersion of academic research has become entangled with allegations that the United States is funding too much research, that such overcapacity is threatening the health of academic research, and that dispersion is leading to diminished quality of research.

Our survey results support the notion that there is considerable geographic dispersion of university-industry research centers. This is shown in Table 3-5 which reports the number and percent share of centers for all fifty states. As this table shows, no state in our sample accounts for more than 10 percent of the total number of centers. The states with the largest number of centers are Pennsylvania with 9.8 percent of the total, Illinois with 6.8 percent, California with 6.1 percent, New York with 5.3 percent, and Texas and Wisconsin with 4.7 percent each. Interestingly, Massachusetts with its concentration of top-tier institutions accounted for just 16 centers or 3.1 percent of the total sample. A large group of states are clustered in the 1 to 3 percent range. Thus, even though out results are only for one point in time, they tend to lend support to the dispersion hypothesis, as centers are distributed across a large number of states with little concentration. Furthermore, while states which are home to leading research universities tend to have more centers on average than those which are not, the differences are not overwhelming.

There are at least three possible explanations for such dispersion. One possible reason is simply the increasing size of the pie, which has enabled some of the wealth to be spread around. A second potential explanation is that universities have come to recognize the economic benefits associated with funded research and have undertaken efforts to attract resources from new sources such as state governments and local industry to launch new centers, recruit leading faculty members, and in extreme cases lure entire centers from other universities, sometimes leading to bidding wars. A third potential explanation which flows from the work of Roger Noll and Linda Cohen on "pork barrel" science and technology is that the distribution of research funding has become more highly politicized over the past couple of decades. Former IBM chief scientist, John Armstrong suggests that the emphasis on industrially-relevant research and the use of competitiveness as a rationale for increased public support for university research has exacerbated the tendency toward "scientific pork," the awarding of research grants and contracts by political officials who increasingly see federal research contracts and facilities as a source of technological and economic advantage.

What Do University-Industry Centers Do?

It is widely thought that university-industry research centers are vehicles for applied research. Some even go so far as to consider them important contributors to economic development. Our survey data enable us to consider the activities and goals that such centers actually pursue.

The university-industry research centers in our sample are highly focussed on research, devoting more than two-thirds (70.2 percent) of their effort to research and development. In addition, they devote 14.6 percent of their effort to education and training, 6.6 percent to technical assistance, 6.7 percent to technology transfer and 2.0 percent to entrepreneurial support (see Table 3-6). They devote a considerable share of their research activity to basic research, with their research effort divided almost equally between basic and applied research, 41.0 percent on average going to basic research and 42.1 percent going to applied research (see Table 3-7). Interestingly, the centers in our sample devoted 16.8 percent of their effort to development, a form of R&D activity which is typically not associated with university-based research. (Our survey used the standard NSF definitions of basic research, applied research and development).

[Table 3-6 and 3-7 about here]

Our research suggests that university-industry research centers devote a greater share of their R&D effort to applied research and development than do universities as a whole. In 1990, universities devoted 65.4 percent of their R&D effort to basic research, 26.7 percent to applied research and 7.8 percent to development. Thus, university-industry research centers devoted nearly twice the relative effort to applied research. However, the proliferation of such centers during the 1980s is not reflected in any change in the composition of university research overall during that period. Indeed, the share of university research devoted to basic research remained stable over that period.

We considered whether the mix of activity between basic research versus applied research and development has changed for university-industry research centers over time, looking specifically at centers founded before 1985. More than half (55.6 percent) of centers report no change in the mix between basic and applied research and development since their founding. For 29.8 percent of centers, the mix has moved toward more applied research and development, while 14.6 percent of centers increased the share of effort dedicated to basic research.

Not surprisingly, university-industry research centers see their primary goal as advancing scientific and technical knowledge. As shown in Table 3-8, 77.3 percent of centers indicated that the goal, "to advance technological or scientific knowledge," was very important, based on a four-point Likert scale where responses vary from "not important" to "very important." The second most important goal was "education and training" with 56.3 percent responding very important. This latter goal is consistent with industry's interest in obtaining trained personnel from university-industry research centers. On a four-point Likert scale (where response categories ranged from one for "not important" to four for "very important"), the mean scores for the two key academic objectives “to advance technological or scientific knowledge” and “education and training” were 3.71 and 3.40 respectively.

[Table 3-8 about here]

The centers in our sample ranked industry's other more tangible and immediate interests considerably behind more conventional academic objectives. Just over only (25.7 percent) of the centers in our sample indicated that the goal of improving industry's products or processes was very important (33.4 percent ranked this goal as important); and 26.0 percent indicated that the goal of transferring technology to industry was very important (37.3 percent ranked this goal as important). The mean scores for these two key industry-related objectives, namely *to improve industry’s products and processes* and *to transfer technology to industry*, were 2.78 and 2.71, respectively. One-third (33.7 percent) of centers saw the goal of demonstrating the feasibility of new technology as very important (and 32.9 percent ranked this as important); the mean score for this objective was 2.91.

Governments, particularly at the state governments, have frequently promoted university-industry research programs and expenditures on the grounds that such university-industry relationships can stimulate regional economic growth. As we have seen, some scholars and policy makers believe that the university can and is playing a more important role in direct economic development. Our findings indicate that, however, that stimulating economic development is less important to university-industry research centers than more academic goals.

Less than 10 percent of the university-industry research centers in our survey reported the creation of new businesses, job creation, or the attraction of new industry as very important goals. Indeed, more than 40 percent of the respondents viewed these economic development goals as unimportant (see Table 3-8).

Differences in these key goals and objectives is surely one of the most important ways that centers differ from one another, and a key difference is the degree to which university-industry research centers attend to the relatively applied needs and concerns of their industrial participants. We examined the degree to which the goals of university-industry research centers affected their allocation of activity and effort. Table 3-9 breaks down the shares of activity devoted to basic research, applied research and development by the importance that centers attach to the goal of improving industry's products or processes. Not surprisingly, university-industry research centers which pursue more industrially-oriented goals devote a much higher share of their activity to applied research, particularly to development. Centers that viewed commercial concerns as unimportant devote the bulk of their activity to basic research, with only a small share of their total effort going to development.

[Table 3-9 about here]

Our findings suggest that more recently established centers tend to have a more applied industrial orientation (Figure 3-2), at least as revealed by the importance they attach to the goal of improving industry's products and processes. For example, only 16.4 percent of centers founded before 1980 indicated that improving industry's products and processes was “very important,” while 32.7 percent of those founded after 1980 ranked this as very important. More than half of the centers founded after 1980 ranked this goal as important. In addition, one-third of the centers (33.0 percent) established between 1980 and 1984 ranked this goal as very important, and an additional 28.3 percent ranked it as important. Of the centers established after 1984, two-thirds ranked it as important, with one-third (33.3 percent) responding very important and another third (33.3 percent) responding important. These figures are consistent with the recent emphasis that funding agencies have placed upon university-industry research relationships as a vehicle for promoting technical advance in the U.S. manufacturing sector.

In short, university-industry research centers differ considerably in their goals and objectives. Perhaps the most salient difference is the degree to which they focus on affecting technological change in an immediate and tangible way that can directly impact industry. While some centers, particularly those founded in recent years, hold that goal quite dear, others are concerned with more purely academic objectives. Furthermore, only a relatively small share of centers emphasize direct contributions to economic development.

Industries, Disciplines and Technologies

The research conducted at university-industry research centers is applicable to a wide array of technological, scientific and industrial fields. More than one-quarter (27.3 percent or

137) of centers conduct R&D relevant to the manufacturing sector exclusively, while more than two-thirds (67.9 percent or 340 centers) conduct R&D that is relevant to both the manufacturing and non-manufacturing sectors. Less than 5 percent (4.8 percent or 24 centers) conduct R&D that is exclusively relevant to the non-manufacturing sector.

The university-industry research centers in our sample are heavily concentrated in so-called high-technology fields (see Table 3-10). Three technology areas — advanced materials, environmental technology and waste management, and computer software — were the most heavily represented, with between 25 and 30 percent of centers pursuing research activities related to these fields. Biotechnology, biomedical technology and energy were the next most heavily represented areas with between 20 and 24 percent of centers pursuing research in these fields.

[Table 3-10 about here]

What about industrial sectors? The number and percentage of centers associated with a given industry is presented in Table 3-11. As these data indicate, the research conducted by university-industry research centers is concentrated in chemicals, including pharmaceuticals (41.7 percent), computers (35.0 percent), electronic equipment excluding computers (29.0 percent), petroleum and coal products (28.2 percent) and software (26.0 percent). No other industry accounts for more than 22 percent of research activity.

[Table 3-11 about here]

We also identifed centers by the academic disciplines waugh which they contribute (see Table 3-12). Biology and chemistry are the most heavily represented of the basic sciences, each of these accounting for more than one-third of all centers. Roughly two-thirds (65.6 percent) of centers are contributing to at least one basic science. Materials science and computer science are the most heavily represented of the applied sciences. Materials, electrical, mechanical and chemical engineering are the most heavily represented of the engineering fields. Each of these is associated with more than one-quarter of centers. These findings are supported by a recent survey of university faculty members in science and engineering, which found that there is a strong disciplinary effect behind the intensity of faculty interaction with industry, with faculty in electrical engineering and materials interacting much more with industry than say physics faculty.

[Table 3-12 about here]

There are also clear differences in the spending patterns of centers by academic discipline, as Table 3-12 shows. At the top of the list are centers conducting research in astronomy ($9.2 million) and atmospheric science ($8.8 million), with more than twice the average or mean expenditures of all centers. Centers conducting research in agricultural science, geology, mathematics, physics and aeronautical engineering also had average expenditures in excess of $6 million. Centers conducting research in biology, chemistry, industrial engineering and computer science had average expenditures between $5 and $6 million per year in 1990. At the low end of the distribution are centers conducting research in medical science and materials science with average expenditures of less than $4 million per year in 1990. It is important to point out that the survey question regarding disciplines was not exclusive. In other words, it did not make center directors choose one discipline or to rank disciplines by the level of contribution, but simply to designate all disciplines to which their center contributed.

[Table 3-12 about here]

University Initiative

In the previous chapter, we discussed how the role entrepreneurial efforts on the part of universities in forging and fostering closer ties with industry. Henry Etzkowitz has argued that the recent rise of increasingly science-intensive industries, such as biotechnology, has given the university more, rather than less, control over its relationships with industry. In his words: "The balance of power between the university and the institutions it has traditionally been dependent upon for support is shifting in favor of the university, as university-based research increasingly becomes the basis of economic development. Therein lie the paradox of entrepreneurial science. If basic research is put aside because of commercial opportunities, it will be the result of scientists' choices. Rarely have a social group had such freedom to establish their own course, and to set the terms on which they will receive the resources to pursue it, as do contemporary academic scientists." Others have argued that this relationships hinges at last to some extent at the quality of the university. Edwin Mansfield has suggested that less prestigious academic departments may be more willing to devote their efforts to commercial goals over basic research. A recent survey of university-industry research centers in the engineering fields by Robert Morgan and his collaborators found that centers which were located at universities with the highest expenditures on engineering research tend to do more basic research, while centers at other universities tend to tailor their research to the more applied preferences of industry. As the previous chapter has shown, universities which are trying to climb up the academic ladder--particularly MIT at the turn of the century, and to a lesser extent Stanford University in the immediate post World War II era--have oriented their research in ways that can attract industrial support.

Our survey provides useful empirical results with which to further explore the notion of the entrepreneurial university. Simply put, the survey results lend additional empirical support to the view that university-industry relations are principally the result of the entrepreneurial university rather than the result of industry initiatives to develop universities as a resource for its own ends. The survey findings clearly indicate that universities—-and university faculty members in particular-—provided the primary, direct impetus behind the formation of university-industry research centers. Almost three-quarters (72.5 percent) of them indicated that the primary impetus behind the university-industry relationship came from university faculty (60.9 percent) or university administrators (11.6 percent). Government provided the primary impetus for 10.9 percent--6.1 percent from the federal government and 4.8 percent from state government; while industry provided the primary and direct impetus for only 10.7 percent. Our survey findings also indicate that industry support was sought to offset what was perceived to be inadequate research funding from government. Indeed, 86 percent of centers indicate that inadequate research support from government was at least "somewhat important" in motivating the center to obtain industry funding. These findings are supported by the results of other, recent research. A survey of faculty members in engineering departments conducted by Robert Morgan and his colleagues found that faculty generally sought increased funding from industry because government funding has become unreliable. They did so even while believing that industrial funding pushes their research in a more applied direction and affords them less control over their own research agendas. As we will shortly see, the same basic point is reinforced in our data as well.

WES IN A PERVIOUS VERSION YOU NOTE THE NEED TO COMBINE OUR DATA WITH UNIVERSITY QUALITY DATA. HAS THIS BEEN DONE

Financing University-Industry Research Centers

How are university-industry research centers financed? What constitutes their principle means of support?

Government was far and away the major supporter of university-industry research centers providing nearly half of their total support, most of coming in the form of cash support. Industry provided roughly 20 percent of support and universities provided almost 15 percent. Approximately 10 percent of university support was in-kind and approximately 8 percent of industry support was in-kind.

Industry spent more than $560 million on R&D at university-industry research centers in 1990. This figure is derived using our estimates of total R&D spending by university-industry centers ($2.89 billion) and industry's share in supporting that R&D (19.5 percent). Industry's R&D contribution of $563 million to university-industry research centers represents almost exactly half (49.8 percent) of its total support for academic R&D in 1990 of the $1.13. However, this comparison should be qualified because the estimates of industry's contributions to university-industry research centers are reported by center directors, not by the firms themselves who report directly to the Census and in turn to the National Science Foundation, which reports overall R&D statistics. Nonetheless, these data suggest that university-industry research centers were the predominant vehicle for industry support of academic R&D in 1990. Industry’s $563 million expenditure on R&D at university-industry research centers represents slightly less than one percent (0.7 percent) of industry’s own-financed total R&D spending of $75.7 billion in 1990. It may be more appropriate to compare industry's spending on university-industry research centers to its basic and applied research expenditures. This contribution of $468 million was equivalent to 1.6 percent of the $28.5 billion industry spent on basic and applied research in 1990.

A substantial fraction of university-industry research centers receive only a small share of their support from industry. Of the 407 centers reporting both budget data and funding source breakdowns, 152 or 37 percent received 10 percent or less of their support from industry, and 89 or 22 percent received 5 percent or less of their support from industry. However, since some centers are very large, 5 or 10 percent of total support from industry may still be significant in absolute terms. For example, 72 of the 152 sample centers with 10 percent or less of their support from industry received at least $50,000 in industry support in 1990.
[WES: YOU MAY WANT TO ADD A DISCUSSION OF IRV FELLER'S POINT THAT CENTERS MAY BE BANKRUPTING UNIVERSITIES BY FUNCTIONING AS LOSS LEADERS THAT DO NOT COME THROUGH SOMEWHERE AROUND HERE]

Government as Catalyst

We have already seen how the evolution of government science and technology policy over the course of the twentieth century has influenced and helped to shape close ties between universities and industries. The results of our survey research shed additional light on the important role played by government in catalyzing and facilitating these relationships. One thing is abundantly clear: Despite their ostensible ties to industry, many centers are chiefly interested in government, not industry, support.

The survey findings overwhelmingly indicate that government is far and away the principal source of support for university-industry research centers. According to our survey, approximately 86 percent received some form of government support, including largely federal but also state support (see Tables 3-14 and 3-15). Government provided more than half (59.9 percent) of their support in 1990, with 45.0 percent coming from the federal government and 14.9 percent coming from the states. However, the share of funding government provided to these joint university-industry research centers is somewhat less than the government's share of overall support for academic research. In 1990, government accounted for 67.2 percent of total academic research funding, 59.0 percent from the federal government and 8.2 percent from state and local government.

Furthermore, government support for university-industry centers comes mainly in the form of cash support. In contrast to the large share of university and industry support that come from in-kind contributions, less than 1 percent of government support was provided in-kind. As Table 3-15 shows, the major federal agencies supporting university-industry research centers include: the National Science Foundation (NSF), Department of Defense (DOD), Department of Energy (DOE), NASA, the National Institutes of Health (NIH), Environmental Protection Agency (EPA) and the Department of Agriculture. All of this leads to a rather basic conclusion. Government is the major source of cash support for university-industry research centers, suggesting that it plays a critical role in such arrangements.

[Table 3-14 and 3-15 about here]

A significant share of university-industry research centers actually seek industry support largely as a vehicle for obtaining government support. Forty-two percent indicate that they obtained support from industry because it was required (i.e., at least "somewhat important") for obtaining government support. Thus, many of the marriages between universities and industry have been encouraged — no less directly supported — by government policy. Given all of this it may be more appropriate to refer to these centers by the slightly clumsier moniker--*government-university-industry research centers.*

When considering the role of government, it is always important to ask: What would happen if government was not involved, or if government support was withdrawn. The important question then is whether government promotion and support is achieving something that would not be achieved in their absence. In this case the question is becomes: Are university and industry incentives such that they would do what they are currently doing without public support? Unfortunately, our data do not allow us to consider whether other formal and informal relationships or activities would substitute for joint university-industry centers in their absence. The data do permit us, however, to consider the effects of government funding on the formation of such centers as well as on their activities. On this note, our findings indicate that 71.4 percent of centers were established either wholly or partially based upon funding provided by the federal or state government. Of those, 82.6 percent (or 59.0 percent of the entire sample) indicate that they would not have been established in the absence of government funding.

Would university-industry research centers that currently receive government support continue their activities in its absence? The simple answer is--only partly. Our survey findings indicate that 38.5 percent would not (Table 3-16). And, of the more than 60 percent that would, the majority would continue to pursue their basic and applied research and educational activities to some degree. The withdrawal of government funds would, however, result in two-thirds of these centers increasing their efforts to obtain more industry support.

[Table 3-16 about here]

This point seems to suggest that government support for university-industry research centers is a substitute for private support, implying that private incentives to support university-industry research centers are not being sufficiently exploited. But, this is only weakly confirmed by the data, however. Approximately 80 percent of the centers that would continue to operate in the absence of government support indicated that they would reduce their basic research without government support. Approximately two-thirds would reduce their applied research activities; and slightly more than half would reduce their development activities. These results reveal what one might expect — that basic research would be the hardest hit by the withdrawal of government support, perhaps because it is least likely to be supported by industry.

Government support has thus been both critical to the establishment of university-industry research centers and vital to their operations, particularly to the basic research component of those activities. While the survey data suggest that government funding is important to the activities of these centers, it raises the question of what is the effect of these activities on the technological progress realized by the industry participants as well as on the research that is conducted by universities. This is the question to which we now turn.

Chapter 4

University Research and Technological Change:

Exploring the Performance University-Industry Research Centers

[Florida Note: NEED TO ADD A CAREFUL, REFLECTIVE DISCUSSION ON WHAT CAUSES DIVERSITY OF OUTCOMES BY TECHNOLOGY FIELD]

> Most industry officials believed that, whereas universities are at the forefront of scientific discovery, product and process oriented technical change occurs within industrial firms for most fields. Industry is the primary source of innovation because industry culture fosters entrepreneurial awareness of profitable emerging field and ideas. In addition, industry scientists and engineers know more about a technology--its detail and its systems--than do academic scientists and engineers. The limited role of universities in innovation has not been recognized because of the misconception that technological change generally occurs through a remarkable breakthrough that will revolutionize an industry, ... and because university scientists tend to have a simplistic understanding of how product development and commercialization occur. ... At the same time, an enormous amount of basic research is being conducted in universities to add to the knowledge base that supports both the processes of incremental technological advance and breakthrough discoveries. How much companies rely on universities, however, varies as a function of the technical field, the maturity of the industry, the stage of the research, and the size of the company. (Government-University-Industry Research Roundtable and the Industrial

Research Institute, 1991).

The role of universities and of university-industry research centers in the process of technological change is an issue that has captured the attention of academics and policy-makers alike. On the one hand, there are those that argue that universities can and should play a more direct role in the development of commercial technology and that closer university-industry research relationships can help accelerate the transfer of university science and technology to the private sector. Some suggest that closer ties to industry may even help to advance some branches of academic science, by pointing to unsolved problems and opening up new pathways for research. Students of the history of the interaction between science and technology argue that work on commercial technology often stimulates important basic science, by focussing attention on heretofore unexamined problems and opening up new lines of inquiry. In their view, a shift in resources toward more applied research and development in the short-run need not undermine basic research in the long run. On the other hand, a number of academics and university administrators contend that increased involvement with industry will tend to push academic research in a more applied direction, foregoing important advances in basic science which may be the source of important, new breakthroughs in the longer run.

As noted earlier, Edwin Mansfield found that the social rate of return to academic research was roughly 28 percent for the ten year period 1975-1985 (Mansfield later revised his estimate to 20 percent), and concluded that about one-tenth of new products and processes commercialized during that period capitalized on recent university research. In subsequent research, Mansfield found that interactions between university and industry are influenced by the geographic proximity of industrial and university research efforts and by the quality of the university faculty involved as well. But, Mansfield's research has been criticized for trying to draw more general inferences about the social return from university research on the basis of only several selected industries. A 1989 study by Adam Jaffe and follow-on work by Jaffe in collaboration with Manuel Trajtenberg and Rebecca Henderson found that industrial R&D tended to locate in proximity to and be stimulated by university R&D.

Others have examined the more direct effects of academic research on technical advance in industry through the use of focussed surveys and case studies. Denis Gray and his colleagues conducted evaluations of centers supported by the National Science Foundation and found that university-industry research centers were more likely to generate information of use to industry in its ongoing research and development efforts than to generate patents or commercial products or manufacturing processes of immediate use to participating companies.

David Blumenthal and his collaborators found industry depends on academic research more for access to ideas, knowledge and new talent than as sources of direct commercial innovation. His 1994 survey of industrial involvement in the life sciences found that 90 percent of companies conducting life sciences research in the United States had research relationships with U.S. universities, and that 59 percent of these firms supported university R&D, providing $1.5 billion in academic R&D funding or 11.7 percent of all university R&D. The most prevalent type of relationships was consulting with 88 percent of firms reporting the use of professors as consultants. Blumenthals's research came to three important conclusions. First, Blumenthal found that 56 percent of companies that supported university research depend on university faculty to "keep staff current with important research," 33 percent depend on them to provide new ideas for products, 37 percent depend on faculty as a source of new recruits, and just 29 percent depend on faculty to invent products that the company will license. Second, Blumenthal's 1984 and 1994 surveys found that industrial sponsorship of university research yielded commercial payoffs which were similar to industrial research and development. Industry sponsored academic research generated returns in patents, products and sales per dollar invested that did not differ significantly from the return to in-house company R&D. Third, Blumenthal's 1994 study identified several obstacles to university-industry research relationships in the life sciences. Roughly half of the firms that responded to Blumenthal's survey noted university bureaucratic procedures which made it unnecessarily complicated to conclude agreements (54 percent of firms) and university regulations that interfered with contract negotiations (49 percent) as serious obstacles to university-industry research relationships. In addition, 33 percent of firms stated that changes in the direction of academic research had reduced its commercial utility and 30 percent reported conflict of interest which developed because the academic institution became involved with another company. Interestingly, 12 percent reported concern of misconduct or questionable scientific practices by academic scientists. It should be noted, as discussed in chapter 2, that life science research, especially in the field of biotechnology, is quite different from most university research in its direct relevance to industry. For this reason, one should be cautious in generalizing the results of Blumenthal's study to other disciplines.

It is increasingly recognized that the interactions of academic science and industrial technology are not uniform but differ considerably by the particular field of technology or industrial sector. Students of the process of scientific and technological change have suggested that the innovation process is distinguished by a complex and multifaceted "division of innovative labor" composed of complementarities and relationships across firms, universities, government and other institutions that facilitate innovation. A survey of R&D executives in 130 manufacturing industries conducted by Richard Levin, Alvin Klevorick, Richard Nelson and Sidney Winter in the mid-1980s examined the way that basic and applied sciences contributed to technological advance in particular industries. Although the survey suffers from some methodological problems, its overall results clearly suggest that division of innovative labor varies considerable across fields. The researchers explored the relevance of research in eleven fields of basic and applied science to each industry's technological progress, as well as the relevance of university-based research for those same fields, and found that the overall relevance of science to technical advance varied considerably across industries. For example, of the 130 industries in their study, they found drugs and semiconductors to be the most closely linked to science in general, that is science taking place in industry and government laboratories as well as universities. Furthermore, they found that biological industries, particularly the medial and agricultural applications of biological sciences, to be most closely linked to research done at universities.

This chapter explores these issues, by examining the performance and productivity of university-industry research centers, looking specifically at their role in the process of technological change overall and by technology field. How do these centers perform? How does performance vary across technology fields? What other factors affect the performance of university-industry research centers? To answer these questions, we present survey data and the results of various analyses of the performance and productivity of university-industry research centers. A main conclusion of our research is that the role and function of university-industry research centers varies considerably across industries and technology fields, and furthermore that their effectiveness lies not just in their ability to generate inventions or patents, but also in helping to improve industry's products and processes and in suggesting new project ideas to industry.

A complete evaluation of the performance of university-industry research centers should include the views of industry on the effectiveness of relationships with universities. To address this issue, we conducted interviews with a series of companies across various field of technologies on the factors that influence their participation in university-industry research centers and that determine the effectiveness of such interactions. We also reviewed existing studies of industrial perspectives on university-industry research relationships. The findings of both our own interviews with firms and this broader body of work is presented in the last section of this chapter.

Performance of University-Industry Research Centers

We begin our analysis of the performance of university-industry research centers by looking at a series of fairly standard measures of innovation. Here, we would like to point out that evaluating the effects of university-industry research centers on the pace of innovation and technical advance is a difficult and complicated undertaking, mainly due to difficulties in constructing reliable and consistent outcome measures, lags in the innovation process, and the complexity of the process of technological change. Nevertheless, there are a series of measures of innovation that can be used to consider the output of university-industry research centers.

We divided the outputs of university-industry research centers into three broad classes. The first class of outputs are direct or *tangible* outputs, such as patents, patent applications, prototypes, copyrights, licenses, invention disclosures, and scientific research papers. Spin-off companies are another type of tangible output. The second class of outputs are *educational* outputs that contribute to the nation's stock of science and engineering human capital. These include Ph.D's and Master's degrees awarded on the basis of student participation in university-industry research centers. The third class of outputs are *intangible* outputs. We refer to this class of outputs as *intermediate* outcomes. Here, we recognize that tangible and even educational outputs do not capture to full contribution of university-industry research centers to the knowledge base and associated activities of participating firms. We turn our attention first to the tangible outputs of university-industry research centers.

University-industry research centers generate a significant amount of tangible output. The centers that responded to our survey reported the following tangible outputs in total: 614 inventions, 419 patent applications, 203 patents granted, 153 licenses, 289 copyrights, 354 prototypes, 259 new products and 341 new processes. It is important to point out that these figures reflect the total number of outputs reported only by the respondents to the survey who reported output; the analogous figures for the entire sample is surely higher and would be considerably higher for the for overall population of 1,056 centers. We have not estimated what these expanded numbers would be because we suspect that the propensity to report output data is positively correlated with output. We also know from more general studies of innovation that output distributions tend to be highly skewed, so that estimations for the entire population based on our sample data might be quite inaccurate.

While total counts of outputs are useful, it is more revealing to examine the average tangible output of university-industry research centers (see Table 4-1). Because of the nature of our survey, we used two techniques to estimate this average output. Accordingly, Table 4-1 reports two averages for each type of output. In analyzing the response to our survey, it was difficult to know whether a blank response indicates zero or is a missing value. To deal with this, we include two estimates of average output. The first average--the lower number in the table--is estimated with the assumption that a blank answer to a question means zero, when a respondent answers at least one item in a question category but leaves the others blank. The second average treats the blanks as missing values. These figures are computed for the entire sample.

As Table 4-1 indicates, the average tangible outputs for university-industry research centers were as follows: 1.00-1.31 patent applications, 0.48-0.66 patents issued, 0.36-0.52 licenses, 0.85-1.28 prototypes, 0.62-0.95 new products invented, 0.81-1.24 new processes invented and 0.69-1.09 copyrights. The medians for almost all of the tangible outputs are zero. The output of research papers was high with the average for 1990 being 35.33-41.84 and the median being 17-20.

[Table 4-1 about here]

Spin-off Companies

University-industry centers can also contribute to technical advance by yielding new process or product ideas that can be commercially exploited through the formation of new enterprises, commonly referred to as *spin-off* companies. As Chapter 2 has shown, universities have developed various mechanisms for promoting and investing in spin-off companies. The survey collected data on the number of such spin-off companies from such centers. As Table 4-2 shows, 21.2 percent of the respondents or 103 centers indicated that new companies have been created as a result of center research activity. These centers generated 245 spin-off companies in total. That means that the average number of spin-off companies for centers that reported spin-off companies was 2.38. Furthermore, 49 centers reported one spin-off company, 30 reported two spin-off companies 15 reported three to four spin-off companies, and three centers reporting 10 to 20 spin-off companies.

[Table 4-2 about here]

There was considerable variation in the number of spin-off companies in various fields of technology, with the largest number of spin-off companies occurring in the fields of computer software and hardware, environmental technology, biotechnology, advanced materials, robotics, semiconductors, and agriculture (see Table 4-3). We also examined the average number of spinoffs per center for each technology field, taking into account both those center which reported spin-offs and those which reported zero spin-offs. Here, the leading technology fields in producing spin-off companies were computer hardware, software, semiconductors, agriculture, computer software, robotics, telecommunications, pharmaceuticals, chemicals and advanced materials.

[Table 4-3 about here]

Educational Outputs

University-industry centers also effect technology change and the broader society through their education and training efforts. In fact, the educational contributions of university-industry centers are considerable. Our data suggest that research conducted at the centers in our sample was the basis for the award of 1,707 Ph.D.s in 1990. That same year, universities nationwide produced 22,857 Ph.D.s in science and engineering. Thus, the research conducted by centers in our sample provided the basis for the award of at least 7 percent of science and engineering Ph.D.s nationwide. On an average basis, research conducted in connection with university-industry research centers is the basis for a little more than four Ph.D.s and approximately seven master's degrees per year (see Table 4-1). Each center employed an average of 14.4 graduate students, 8.2 undergraduates and 2.8 postdoctoral fellows in 1990 (see Table 3-2 above). Also, as noted earlier, a significant number of university faculty, researchers and students nationwide are exposed to center activities. Thus, university-industry research centers make an important contribution to the economy and society through their education and training effort.

University-industry research centers also play an important role in providing trained employees to industry. The field research and interviews suggest that a key motive for industry participation in such centers is to gain access to a pool of trained, technically competent prospective employees who have gained practical experience as well as academic training. The survey findings indicate that centers play an important role in providing trained employees to industry. On average, 5.70 students from each center received permanent employment from participating companies in the two year period, 1989-1990, with 58.3 percent of the respondents indicating that at least one student had been employed by a participating firm in 1989 or 1990. (The mean employment for the two year period 1989-1990 for centers founded before 1987 was 6.36 and the median was two.) Slightly more than half (50.4 percent) of centers indicated that they provided industrial participants with privileged access to their students as prospective employees. In addition, 37.8 percent of responding centers indicated that "practical experience for students in an industrial setting" was a benefit from their relationship with industry.

Intermediate Outcomes

As noted above, we developed a class of intermediate outcome measures to reflect the intangible effects of university-industry research centers on the R&D activities of participating firms. Although measuring tangible outputs such as patents, inventions and prototypes is useful and important, such measures do not fully capture the effects of university-industry research centers on technological advance. In particular, such measures do not capture the full contribution of these joint centers or similar organizations to the knowledge base and associated

R&D activities of participating firms. Taking this into account, we developed a series of intermediate outcome measures to assess better the effects of university-industry research centers on technical advance. The concept of an intermediate outcome refers to the effect of the knowledge generated by university-industry research on the R&D activities of firms. In particular, we were concerned with the ways firms used the research from university-industry research centers to revise their own views of the feasibility of particular technologies, make their own R&D process more efficient, and make improvements in existing products and processes. Accordingly, the survey asked the center directors to indicate, to the extent possible, how frequently knowledge produced by their centers was used by participating firms in 1990 to: (1) improve existing products, (2) improve existing processes, (3) introduce new products, (4) introduce new processes, (5) make existing R&D projects more efficient, and (6) introduce altogether new R&D projects.

Although this third class of intermediate outcomes offers the important advantage of recognizing what some believe to be among the most important contributions of university-industry research centers, and universities more generally, to technical advance, our measures are subject to several potential problems. First, these measures are especially subject to measurement error, simply because they are subjective. Thus, these responses are likely to be prone to inter-rater differences in how each of the six intermediate outcome measures are defined. Furthermore, there may be systematic relationships between this measurement error and selected attributes of university-industry research centers such as size or age. For example, follow-on discussions with center directors indicate that what they might have considered a contribution to a participating firm's research and development efforts when their center was young, they no longer consider when their center is older and they have more experience. Because center size and age are positively related, this age-related error translates into a size-related error. Third, we expect directors of smaller centers to have reasonably good knowledge of the center's intermediate outcomes, but directors of large centers would be less likely to have such complete knowledge. Finally, participating firms are obviously more qualified to answer this question than the center directors who responded to our survey. Nevertheless, university-industry research centers provide an important source of information on this issue. Indeed, the center directors who were allowed to indicate that they did not know the answer on the questionnaire, and between 36 and 44 percent of respondents did so, depending upon the specific question. With these qualifications in mind, we now consider these outcomes, simply because there is no other measure to capture these intangible effects.

Our findings regarding intermediate outcomes are summarized in Table 4-4. These findings indicate that university-industry research centers principally contribute to the improvement of existing processes or products and increase the efficiency of existing R&D projects. The centers in our sample typically realized each of the six types of intermediate outcomes between one and five times. As Table 4-4 indicates, the mode and median values for all six types of intermediate outcomes fall in the range of one to five times, or three times if the mid-point is used. Centers contributed to the improvement of new products and processes and to the increased efficiency of existing R&D somewhat more than they contributed to the introduction of new products or processes or the introduction of new R&D projects by industry. Furthermore, we would like to point out that the results indicate that of those respondents claiming they could answer, between 13 and 21 percent of responding centers, depending upon the particular measure in question, reported that they never observed a given effect. Of the 190 centers that indicated they could respond to all the intermediate outcome questions, 6.3 percent indicated that none of these outcomes had ever been realized by participating companies.

[Table 4-4 about here]

It is important that the reader understand that for any of the outputs we have considered above and consider in more detail in this and the following chapter, we are not able to discern important differences between outputs of the same type from our data. In other words, because we only the number of outputs for each center, we do not know anything about how these outputs might compare to one another. Thus all papers, patents, new products reported *etcetera* are treated equally, and yet we know from other studies of innovation that the scientific or commercial value of different research projects is very skewed. In addition to differences in intrinsic value, different outputs of the same type may be qualitatively different from one another, and these differences may be systematically associated with various UIRC characteristics. Lack of data on such differences for the UIRC outputs reported in our data represents one of the principal limitations of our study.

Productivity

While measures of average output are important and revealing, such measures can be misleading, particularly if there are large differences in the size of individual university-industry research centers. To account for this, we normalized all of our output measures to examine the output of university-industry research centers to take into account differences in center size. Initially, as reported in the 1994 report by Cohen, Florida and Goe, we reported average center productivity defined as output per million dollars. These results are presented in Table 4-5 which presents center productivity per $10 million dollars of expenditure. In reporting output and performance results for the rest of this chapter we adopt the conservative convention discussed above by which blank responses are treated as zeros when respondents answered at least one item in the tangible and educational output categories. Using the more conservative of these two measures, we still find centers to be reasonably productive. As Table 4-5 shows, centers generated an average of 221 research papers, 10.4 new inventions, 5.4 copyrights, 11.2 prototypes, 8.0 new products, 7.2 new processes, 7.5 patent applications, 4.2 patents, and 2.3 licenses per $10 million in expenditures. Also indicated in Table 4-5 is center productivity for educational outputs, which is 30.9 Ph.d and 56.5 master's degrees per $10 million dollars of expenditure.

It should be noted that we do not consider copyrights and licenses to be reliable measures of the productivity of center research per se. Licenses are more often the result of downstream efforts by administrators within university patent and license offices and do not generally reflect the activity of academic researchers. Indeed, a number of the faculty we talked to, as well as a number of the line managers and bench scientists in industry expressed considerable frustration with the way these offices handled the licensing of results from academic research. Copyrights, on the other hand, are put on any copyrightable material, including computer code, at the discretion of the author, and provide little, if any, indication of the level of research accomplishment associated with that material.

[Table 4-5 about here]

We also examined the production of intermediate outcomes per $10 million dollars. In computing the productivity for the intermediate outcomes, we needed to account for the right censored quality of the data. Unlike the two other classes of outputs for which we had specific numerical responses, for the intermediate outcomes, we asked respondents to choose from the following categories: zero, 1-5, 6-10, 11-15, and greater than 15 times. To compute the average productivity for these intermediate outputs, we used the midpoints of each category and dropped all observations in the highest, open-ended category of greater than 15. We did this because, by including it, we would tend to arrive at very low productivity for the largest centers which would be disproportionately represented in this category. This led to very few observations being dropped, never more than six percent of respondents. Also an issue was the fact that the survey question that elicited the intermediate outcome data was phrased that each time a center thought it had an impact on a participating firm, that would count as one output. Therefore, the number of outputs could well rise with the number of participating firms; and firm participation tended to be disproportionately higher for smaller centers. For example, the number of centers participating tended to decline noticeably as center size increased. To control for this, we normalized the intermediate outcome measures by the number of participating firms per center. Thus, our intermediate outcome productivity reported in Table 4-5 actually reflect the number of outputs per $10 million per participating firm.

The results of this analysis indicate that intermediate outcomes are substantial, although it is difficult to know exactly how important these contributions are since we have little basis for comparison. According to this analysis, university-industry research centers reported that knowledge generated in centers yielded an average of 12.0 improvements in existing products, 10.5 improvements in existing processes, 8.6 new product introductions and 6.0 new process introductions per $10 million dollars of expenditure per firm. Centers in our survey reported that knowledge generated by the center was used by industrial sponsors as a basis for introducing 12.6 new R&D projects and helped to make their sponsors' R&D more effective an average of 12.8 times.

Our more recent research and analysis suggested that there are pitfalls to measuring the productivity of university-industry research centers as a function of expenditure. The reason is that expenditures are an inadequate and biased measure of effort. The outputs that centers produce are likely to result from faculty and other personnel whose costs are not fully covered by the center. In other words, centers are likely to claim the entire output of individuals that they only partially support, in effect leveraging off the resources of the broader university environment. Analysis of our data shows that this tendency to leverage outside or partly supported personnel is associated more with small centers than large centers. Furthermore, unlike firms, university-industry research centers are not stand-alone organizational entities with clear and well-defined boundaries. They exist within universities and the boundaries between them and the university environment in which they reside are extremely porous. As a consequence, there may be considerable ambiguity with regard to participation in a center versus participating in the broader university setting.

In light of the *porous* organizational boundaries of university-industry research centers, we believe that it is considerably more accurate to evaluate the productivity of such centers as a function of the number of personnel associated with the center rather than by expenditures. We have found that center directors tend to report outputs from those faculty and other personnel associated with the center notwithstanding the degree to which those individuals are supported by center funds. Our data and analysis indicate that larger centers support a greater fraction of the salaries of their personnel than smaller centers, but this does not have an effect on productivity estimates that are computed on the basis of the number of personnel.

In our survey questionnaire, we asked center directors to report the number of faculty, research scientists, post-doctoral fellows, graduate students, and technical and support staff associated with the center. The problem however is that the research contributions from different types of personnel are obviously not equal. To control for differences in research contribution across types of personnel, we developed an accounting scheme to create an aggregate personnel index. To do so, we essentially computed an exchange rate to reflect the *faculty effort equivalent* for graduate students and other types of personnel. Using a method that was suggested by the center directors interviewed over the course of this study, this exchange rate was determined simply by the ratio of the median salary or other financial support for each personnel type other than faculty to the median faculty salary in a given technology area. For example, if support for one graduate student represents 25 percent of a full-time faculty member, each graduate student counts as one-quarter of a faculty member. Separate exchange rates were computed for each personnel category in each technology area.

In addition, we computed center productivity statistics by dividing the total output for all centers by the sum of all the personnel in those centers rather than by averaging productivity values across centers. We did so for two reasons. First, because most of the university-industry research center outputs we are looking at are rare, using unweighted averages computed on a per center basis would yield extreme values associated with the smallest centers. These values would in turn skew the results. Second, using a procedure of computing average center productivity would give us just that--average *center* productivity. We believe it is more accurate to use the *individual* as the unit of analysis and report the average productivity per individual (or personnel unit) rather than the average productivity per center. The issue here is not entirely statistical. Rather, the crux of the issue is whether the output of centers should be attributed to the action of unified, well-delineated organizational entities (which would be appropriate if we were considering the output of an industrial research and development lab), or to collections of largely autonomous individuals or teams directed by university faculty members. While this is surely a matter of degree, our discussions and field research suggest that the latter characterization is more accurate. For the most part, university-industry research centers look more like university entities than industrial R&D laboratories.

Our measures of the productivity of university-industry research centers on a per person basis are reported in Table 4-6, which reports center productivity per 100 researchers. Here again, centers appear reasonably productive across all classes of output, producing 84 research papers, 3.4 inventions, 1.6 copyrights, 2.0 prototypes, 1.5 new products, 2.0 new processes, 2.4 patent applications, 1.2 patents, and nearly 1 license per 100 researchers. Centers generated an average of 10 Ph.D and 16.2 master's degrees per 100 researchers.

With respect to intermediate outputs, centers generated an average of 1.3 product improvements, 1.6 process improvements and a little more than 2 R&D project improvements per 100 researchers per participating company. Center researchers introduce new products at a rate of 1.3 products per 100 researchers per firm, new processes at a rate of about 1 new process per 100 researchers per firm, and new R&D projects at a rate of about 1.7 new projects per 100 researchers per firm.

Performance Benchmarks

We developed a series of comparative measures or *performance benchmarks* to compare the performance of university-industry research centers to other organizations such as industrial research and development laboratories or universities in general. While appropriate benchmarking data is unavailable for most of the performance indicators in our survey, there are a few relevant measures, such as patents and research papers, for which such benchmarking data are available.

Patents are perhaps the most important dimension for which accurate benchmarking data can be obtained. Patent data are available both for industrial firms and universities. While the following calculations are crude, the results are revealing. In 1990, about 60 percent of the centers in our survey reported how many patents they were issues. These 308 centers reported a total of 203 patents. That same year, the total number of patents granted to universities was 1,174. Thus, the reported patent output of the sample centers was equivalent to a little more than

17 percent of the total number of patents granted to universities nationwide. The patent performance of centers is at least comparable to that for universities as a whole. In 1990, university-industry research centers generated 0.178 patents per million in R&D spending. Universities generated 0.072 patents per million dollars, dividing the total 1,174 university patents by $16 billion in university spending on scientific and engineering R&D. This figure rises to 0.21 patents per million when we divide the total 1,174 patents by the $5.66 billion universities spent only on applied scientific and engineering R&D. Here, it is worth noting that we calculated the patent productivity for centers by dividing the total number of patents by the total R&D spending. Centers which reported both innovative outputs and R&D expenditures produced 152 patents and spent $855.3 million on R&D.

It is perhaps even more illuminating to consider the patent productivity for centers versus industrial R&D laboratories. The patent productivity for centers was approximately one-third that of industrial R&D. In 1990, U.S. companies accounted for 33,359 patents and spent $64.4 billion on R&D. Thus, industrial firms generated 0.52 patents per million dollars of total U.S. corporate R&D expenditure. This gap is understandable since industry's incentives to patent are typically greater than universities'.

A second area where reasonable comparisons can be made is research papers, although here the comparison is restricted to universities. In 1990, the centers in our sample generated 13,992 research papers. Based on that, we estimate that all 1,056 university-industry research centers nationwide may generate as many as 37,000 research papers. To compare, the most recent available data indicate that scientists and engineers engaged in R&D at universities generated roughly 141,000 articles in 1989. This comparison must be qualified by two important facts. First, the National Science Foundation data on university research paper publication tracks only a fraction of all refereed journals, thus the 141,000 figure for all universities is an underestimate. Second, the centers in our sample are reporting research papers, while the data for universities reflects published papers only. University-industry research centers generated 14.4 research papers per million dollars of expenditure in 1990, when we divide the 11,781 papers reported by the 328 centers that produce any innovative output by $816.0 million in expenditures. This compares to 9.4 published articles per million dollars of R&D spending for universities nationwide.

Diversity and the Division of Innovative Labor

As outlined above, the innovation process in general, and the process of scientific and technical advance in particular, are characterized by a division of labor, a set of relationships among firms, universities and other institutions. As we have also seen, students of the innovation process suggest that the division of labor varies considerably across various field of technology. Furthermore, as Chapter 3 has shown, there is considerable diversity or heterogeneity among university-industry research centers. In this section, we consider the way the diversity of types of centers effects the performance of those centers. We suggest that performance of university-industry research centers is likely to differ across dimensions such as size, source of funding, mission, academic discipline, the industries with which they collaborate and the focus of their activity. We also suggest that different types not all centers will emphasize the same dimensions of performance nor produce the same types of outputs. Centers focussed on advancing basic science in the biomedical field may well concentrate on producing academic papers and reports, while centers which focus their activities on developing new generations of software are likely to generate new products and prototypes. While space limitations prevent us from disaggregating centers along every possible dimension of interest, it is useful to distinguish output and productivity by center age, the goals center's pursue, by technology areas, and by the presence of local industry R&D and manufacturing.

Lags

The innovation process is characterized by a lag or gestation period. Accordingly, we may observe productivity differences between new and old centers that are not due to difference in research efficiency across center age classes, but rather are a result of such lag effects. Indeed, since a number of the outputs we are studying might be associate only with centers, and not traditional academic research, we would expect to find a lag between the date of their first generation by a center and the date of center formation. For example, if designing new products is not something academic researchers do, but only begin such work after a center is formed, we would expect older centers to have developed relatively more new products than younger centers. On the other hand, writing research papers is something that center researchers were very likely doing before any centers were formed and so we would consider it less likely to find a lag effect in the writing of research papers. However, if center formation has an effect on the productivity of academic researchers, then we might observe a lag effect even for papers.

In order to investigate this issue we compare the productivity of centers founded before 1987 to that of centers founded between 1987 and 1990 using both measures of productivity. These results are reported in Table 4-7 and 4-8. Looking first at Table 4-7 were we examine average center productivity normalized by dollars we find, somewhat surprisingly, that newer centers are more productive in the generation of all output types, including intermediates, except patents issued and copyrights. In other words, we do find evidence of a lag effect, but in fact find newer centers to be more productive. Since we know that the average center productivity measure based on dollars of expenditure is biased in favor of small centers, and younger centers are more likely to be small, this result may come about because of our measure of productivity.

Table 4-8 indicates that the results of Table 4-7 are robust when we look at productivity by individual researcher. We again find that the newer centers are more productive in all output categories except licenses and copyrights. While some of the differences appear large, a production function based econometric analysis of center research activity (more details below) reveals that the lags effects, including those of the intermediates, are in general not statistically significant. This result is somewhat surprising because it suggests that the research activity and outputs of academic researchers does not change much when centers are formed. Of course, it may be the case that the qualitative character of center output changes when centers are formed, and we cannot measure this type of change from our data. Some of our field work indicates that this in fact the case with center research. Some faculty and directors indicated that when formal ties with industry began, they character of their work often changed in ways that reflected the needs and direction of industry R&D.

[Tables 4-7 and 4-8 about here]

Technology Fields

The fields of technology in which university-industry centers focus their activity are also likely to affect the magnitude and types of their outputs. For example, an output which is common in one field of technology may be less relevant to another. Studies of industrial R&D, for example, suggest that the propensity to patent varies considerably across technology areas. Furthermore, some technology areas may lend themselves more readily to prototyping, product improvements or process improvements. When comparing productivity across technology areas, then, it is not reasonable to infer that centers in some areas are actually more efficient than those in other areas. Rather these figures often reflect the fact that some outputs are more relevant to some areas than others, and some areas may lend themselves to one type of output versus another. Also, the same type of output, such as prototypes for example, may be quite different across areas.

Tables 4-9 and 4-10 present productivity for eight key technology fields: advanced materials, biomedical, biotechnology, computer software, computer hardware, and semiconductors, manufacturing, and environmental technology (see Appendix 4-A). As these tables show, there are clear differences in productivity along selected dimensions of output. These tables also indicate differences between our two productivity measures. These differences between the two measures arise because of center size differences across technology areas. Because of these size differences and their effect on productivity measurement, we will focus on Table 4-10 that reports productivity per person within centers.

For patent productivity, advanced materials and semiconductors are the leading areas. Advanced materials is also the leading area for new products, while biotechnology and environmental technology lead in the development of new processes. Computer hardware leads in prototypes. For academic output, the biomedical area leads in research paper productivity with nearly double the output of the lowest ranked field on this dimension, computer software. Taken together, these findings indicate that types of output vary considerably by field of technology. In chapter 5 we will revisit differences across technology fields when considering UIRC policies regarding research, intellectual property and disclosure policies.

[Table 4-9 and 4-10 about here]

Size

Another important dimension where the performance of university-industry centers is likely to differ is size. To explore the effects of size, we conducted an initial analysis reported in our 1994 report by simply comparing the productivity of small centers (those with expenditures of $500,000 or less) with that of large centers (those with budgets of greater than $500,000). The results of that analysis appeared to suggest that centers with annual expenditures of a half million dollars or less were considerably more productive than centers whose budgets exceeded that figure for every type of output we examined. According to that initial analysis, the productivity of small centers, depending upon the output dimension selected, was from two to six times greater than large centers (see Table 4-11). In the text discussing those results, we cautioned the reader not to infer that smaller centers were actually more productive because there were reasons to believe those original results were artifactual. One of the reasons was that smaller centers were conceivably leveraging more from university resources than their larger counterparts which were more self-contained. One way that might occur is if smaller centers covered less of participating faculty and other staff salaries than larger centers. As noted in the above discussion of productivity measurement, expenditures do not accurately reflect the effort expended to produce outputs, and in fact, are on average underestimates of effort for small centers.

The results change considerably when the more accurate measure of center productivity per person is used, as Table 4-12 shows. In clear contrast to the earlier result, there is no longer a clear pattern suggesting that small centers are more productive for every type of output. For tangible commercial outputs, from invention disclosures through patents, the average center productivity is quite similar for large and small centers. The only exceptions are new product introductions and prototypes for which smaller centers are about twice or three times as productive as their larger counterparts, respectively. Larger centers are slightly more productive in generating research papers. There is little difference between large and small centers in terms of educational outputs, namely Ph.D.'s and Master's degrees. It is only for the third set of intermediate outputs that we find a significant pattern in favor of small centers. Here, similar to the original results, smaller centers appear two to eight times more productive than larger centers. Given the number of reservations we have regarding the intermediate outcomes, we are skeptical of these results regarding intermediate outcomes.

[Table 4-11 and 4-12 about here]

To further probe the effect of size on center performance, we conducted a series of production function regression analyses to explore the effect of size on each of our productivity dimensions, while controlling for important factors that might condition center productivity. Included in this list of factors were differences associated with technology field, the character of research conducted at centers, and academic research quality. These regression analyses indicate that once we control for other factors that can affect center productivity, we find that most center research exhibits constant-returns-to-scale. In other words, center size has no systematic effect on center productivity. There are two exceptions to this constant returns result. First, the production of invention disclosures by centers shows consistently increasing returns-to-scale. In other words, centers are more and more productive at generating invention disclosures as more and more people are added to the center. This result provides a strong rationale for center formation and for conducting this type of inventive research at universities within centers. Second, we find no measurable relationship between size and productivity for the most industrially relevant outputs of centers: new products, new processes and prototypes. We do know from out field work that the type of research that leads to these downstream outputs is often team-based, and that many researchers within centers are often not affiliated with these teams. Since we have no way of measuring who is on a team and who is not from our data, we cannot accurately measure the level of center effort being applied to the development of these downstream outputs, and can thus draw no conclusion regarding the effects of size on center productivity with respect to these outputs. **[Wes, these results are from my thesis, in which I analysed only 6 of the tangibles. Should I do the rest (new processes, MSs and PhDs)?].**

Recall from our earlier discussion regarding the absence of any observable lag effects that we indicated that the qualitative character of center outputs may be different from that of traditional individual investigator-level research and that we cannot evaluate these differences from our data, other than by field work. It should similarly be noted that the qualitative character of center output may change as centers get larger. Thus, out constant returns-to-scale results do not indicate that size is irrelevant to center output. Indeed, our field work indicates that some of the larger centers in our sample work on large-scale systems type projects (e.g. large scale robotics projects) that could not be easily conducted by smaller centers much less individual investigators. In fact, some of these centers were formed precisely to tackle these large scale research projects not routinely found in academia.

Goals

Among the more important factors that might condition center productivity across different output types are the goals of center researchers. One goal particularly relevant to the study of UIRCs is the goal of improving industry's products and processes. Center directors were asked to rate the importance of this goal from not important (1) to very important (4). Tables 4-13 and 4-14 report the productivity of centers according to how important this goal was. Because the centers with the greatest levels of industry funding, and thus those centers that generally consider the industry goal as important are smaller than average, productivity measures based on outputs per dollar will be somewhat misleading. Accordingly, we focus on the results reported in Table 4-14.

We find not unexpectedly that researchers at centers that do not consider improving industry's products and processes to be very important are much more productive producers of research papers than those who give any importance to the industry goal. For almost all other tangible output categories, however, those centers that consider the industry goal as very important are the most productive. The two exceptions to this pattern are copyrights and new processes, where we find the most productive group of centers to be those that consider improving the products and processes of industry to be important but not very important. We also find this group to be the most efficient group of centers when it comes to the production of graduate degrees conferred on the basis of center research. The intermediate output categories are much harder to interpret. Surprisingly, the affects of industry friendly goals shows no systematic pattern with respect to intermediate output productivity. This result may simply reflect the problems we know to exist with our intermediate output measures that we have already discussed.

[Wes, the following is some language on the issue of industrial orientation being captured by many measures, including the personnel inputs]. In the course of our productivity regression analyses we found that the effects on center output of different goals was captured by controlling for other aspect of center policy and activity that one would associate with the importance to a center of improving industries products and processes. In fact we found more generally that the overall "industrial orientation" of centers manifested itself in a number of ways, and that the "importance of improving industry's products and processes" appears to capture in an overall sense this industrial orientation. For example, we found that when we controlled for the level of center effort devoted to basic research, applied research development, technology transfer, and joint R&D, as well as for whether or not centers allowed firms to have information deleted from center publications, the inclusion of the variable relating to the center goal of improving industry's products and processes added no explanatory power within a regression framework. Our findings go further than that, however.

One of the main ways in which center industrial orientation is exhibited is in the employment of different types of personnel. The UIRC data tell us how many of six different types of research personnel are employed by centers: faculty, research scientists, post-doctoral fellows, technical and support staff, graduate students and industry scientists resident at centers. It turns out that the composition of UIRC research staff is correlated with the various measures of industrial orientation as well as with the "importance of improving industry's products and processes" variable. Furthermore, the various other measures of industrial orientation, such as the composition of R&D and related effort, the conduct of joint R&D and the disclosure restriction and intellectual property policies are correlated, to varying degrees, with one another. This means that when we include all of them as regressors in a production function analysis we are not likely to observe many independent effects for these variables. Again, this situation arises because each of these variables are essentially measuring the same thing, namely the industrial orientation of centers. In order to avoid this general problem when considering the effects of any one factor on productivity we included it alone as an independent variable in a regress analysis. When we did this for the overall measure of industrial orientation, the response to the survey question regarding the importance of "improving industry's products or processes" we found the this factor has a significant positive effect on the prototypes and new products and especially on the intermediate outputs, and a negative effect on the productivity with which research papers are generated. For the remaining outputs there were no statistically significant effects one way or another. **[Wes, I haven't run any regressions on licenses and copyrights since they are such bogus numbers, but they are in the tables everywhere in the book. Let me know if you want them run].** In the next chapter we will look more closely at the effects of other measures of industrial orientation have on productivity, namely center decisions regarding the amount of basic research conducted, the allowance of disclosure restrictions and intellectual property have on performance.

[Table 4-13 and 4-14 about here]

Summary Discussion:

Overall we find that a number of different factors can affect center performance, and that these factors can affect the production of different center outputs in different ways, sometimes in surprising ways. We find, for example, little evidence of lag effects on center output, although it may be the case that it is the qualitative nature of university research that changes when it is conducted in centers, and not the quantity of different types of outputs. We also find that the relative productivity with which centers produce outputs of different types varies from field to field. Some fields are relatively more productive in the generation of research papers, others in the production of more downstream outputs (e.g. patents, new processes and prototypes) and some in both.

Our size analysis shows that size does not have a very significant effect on center productivity, except for maybe invention disclosures where we find evidence from regression analyses of positive returns-to-size. The fact that the most downstream outputs of centers, new products, new processes and prototypes are often developed in teams that the entire center does not participate in makes analysis of the effects of center size on productivity for these outputs difficult and so we draw no firm conclusions here.

Finally, we find not surprisingly, that center productivity in traditional academic output -- research papers -- decreases for centers more interested in improving industry's products and processes but that these centers are more productive in the generation of the most downstream outputs of centers: new products, new processes and prototypes. Finally with respect to the effects of center goals, we find that center interest in improving the products and processes of industry is positively associated with the most downstream outputs of centers, prototypes, new products and intermediate outputs, negatively so with more traditional academic output, research papers, and has no strongly observable relationship with the production of other center outputs.

The Role of Proximity

The role of geographic proximity in innovation, technical advance and technology transfer is an issue that has attracted increasing attention from students of the innovation process, as well as economists, economic geographers, and organizational theorists more generally. Paul Krugman has called attention to the role of proximity in economic growth, and there is a long tradition of economic geographers who have documented the role of proximity and agglomeration in regional growth and development. A number of economists have examined the effects of proximity between university and industrial research and development. Adam Jaffe found considerable productivity effects associated with proximity between industrial and university R&D, a result that was later supported by Mansfield, Acs, Ausdretch and Feldman, and the Government-University-Industry Research Roundtable and Industrial Research Institute.

As a first cut on this issue, we examined to what extent university-industry research centers are related to local industrial and technological capabilities (e.g. locally-based manufacturing establishments and/or R&D laboratories). The average number of participant companies with local R&D laboratories was 5.70, and the median was one, while the average number of companies with local manufacturing facilities was 5.33, and the median again was one. These figures compare to an average number of participant companies per center of 17.6

and a median of six.

We also examined to what extent centers produce local spin-off companies. Not surprisingly, there was an apparent local bias in the creation of spin-off companies. Of the 103 centers that have created spinoff companies, 84 have done so in the local metropolitan area. The presence of sponsors with local R&D and manufacturing has a considerable effect on the production of new spin-off companies. Centers whose industrial sponsors had either local R&D or local manufacturing units generated considerably more spin-off companies than those whose industrial sponsors did not. Centers whose sponsors had local industrial R&D laboratories generated 160 spin-off companies, an average of 6 spin-off companies for every ten centers, compared to 63 spin-off companies for centers whose sponsors did not have local R&D units, an average of 3.5 spin-off companies for every ten centers. Centers whose industrial sponsors had local manufacturing plants generated 159 spin-off companies, an average of 6.4 spin-off companies for every ten centers, compared to 59 spin-off companies, or 3.3 spin-off for every ten centers, for centers whose sponsors did not have local manufacturing plants. It should be noted, of course, that a number of these local companies with R&D or manufacturing facilities may in fact be the spin-off companies in question, and so one is cautioned against drawing too strong a conclusion regarding the effects of proximity to local industry on the propensity for spin-offs from university research.

To get a better handle on the effects of proximity on university-industry research centers, we compared the performance and productivity of centers whose industrial sponsors had either R&D laboratories or manufacturing plants located in close proximity to the center (see Tables 4-15 and 4-16). Tables 4-15 and 4-16 show that the presence of industrial sponsors with local R&D laboratories or local manufacturing facilities is associated with higher center productivity for virtually every tangible output when productivity is measured both in terms of average center output per dollar of expenditure and in terms of researcher productivity. In fact the only two exceptions to this rule is for the effects of local manufacturing on new products invented when productivity is measured in terms of outputs per dollar of expenditure, and on research paper production for individual researchers.

Looking at the results of Table 4-16, we find that centers with participating companies with local R&D or manufacturing facilities are typically 50 to 100 percent more productive for all tangible output categories except research papers. Centers with sponsoring companies with local R&D facilities are about 10 percent more productive at generating research papers, and those with sponsoring companies with local manufacturing facilities are only slightly less productive in this regard. The positive effects of proximity are apparent for the educational outputs as well, with centers with sponsoring companies with local R&D and manufacturing facilities more productive for both Ph.D and master's degrees for either productivity measure.

What is perhaps most surprising about the results of Tables 4-15 and 4-16 is that proximity appears to have a negative effect on the use by firms of center intermediate outcomes.

However, when we examine the effects of proximity of both firm R&D and manufacturing facilities we find that proximity again has an positive effect on almost all outputs, including research papers and the intermediate outputs.

[Tables 4-15 and 4-16 about here]

Technology Transfer

Up to this point, we have explored the performance and productivity of university-industry research centers in the process of knowledge production. Another issue involves the efficacy of various strategies for transmitting knowledge to industrial firms, and for achieving organizational integration between university and industrial participants in centers. More specifically, it is clear that the effect of university-industry research centers on technical advance depends upon the transfer of knowledge and ideas from the center to industry participants. In our survey, technology transfer was defined as the communication of scientific and technological knowledge resulting from center projects to private companies where it could be used for industrial applications. As indicated in Table 3-8 above, almost two-thirds (63.3 percent) of centers scored the objective of transferring technology to industry as at least "important." However, only 6.7 percent of overall center effort is allocated to technology transfer (see Table 3-6 above).

While the literature on technology transfer is considerable, very few studies provide sufficiently broad empirical evidence from which to gauge the relative effectiveness of various technology transfer mechanisms. Table 4-17 reports the use and the relative effectiveness of technology transfer mechanisms at the university-industry research centers in our sample. Not surprisingly, research papers and reports, telephone conversations and informal meetings were cited as the most commonly used mechanism of technology transfer. Seminars, workshops and joint R&D projects were also widely used.

[Table 4-17 about here]

The survey asked the respondents to evaluate the effectiveness of different technology transfer mechanisms. In considering these findings, it is important to note that the technology transfer mechanisms we consider do not operate independently of one another. For example, a prototype may be delivered along with a technical report, and telephone conversations typically precede and follow face-to-face meetings. To the extent that these mechanisms operate in conjunction with one another, looking simply at the effectiveness scores for any single mechanism may be misleading. Moreover, the differences across the various technology transfer mechanisms are small. We should also point out that our effectiveness scores are computed only for those centers that have used a given technology transfer mechanism.

It is frequently argued that technology transfer is most effectively accomplished via face-to-face interactions and moreover through the transfer and/or rotation of personnel from industry to university and vice versa and the establishment of truly joint and collaborative projects. This perspective was reinforced in our field research, where representatives of both industry and universities noted the difficulty of achieving organizational integration and effective technology transfer. One of the center directors we interviewed early on in the study made the point this way, noting: "We at the university can have our transmitters blasting out new information, yet it will amount to nothing if the receivers are off back at the firms." Our survey data indicate that the most effective (more accurately the most highly ranked by center directors) technology transfer mechanisms include collaborative R&D, having industry personnel work within the center, delivery of prototypes or designs, having center personnel work in industry labs, and informal meetings between industry and university personnel. The respondents indicated that the traditional ways of transferring academic findings, namely research papers and technical reports and seminars, were not as effective as these other mechanisms, and roughly as effective as telephone conversations. In summary, the results appear to reinforce the view that personnel transfers and face-to-face interactions are the most effective component of technology transfer from research centers to industry.

The survey also asked center directors to assess the relative effectiveness of interactions between university and different types of industry personnel for technology transfer. This question was framed in terms of a similar four-point Likert scale. Here, the data indicate that interactions with bench scientists and engineers in central R&D laboratories (39.1 percent responding very effective) and the directors of such laboratories (32.9 percent responding very effective) were seen to be most effective. Another 22.0 percent of respondents indicated that interactions with bench scientists and engineers at development laboratories associated with manufacturing units were very effective. Not surprisingly, interaction with top executives was seen to be relatively less important (just 18.4 percent responding very effective). Interactions with engineers and technicians in actual manufacturing operations were reported as least effective with just 13.9 percent responding very effective.

Our survey findings suggest that the means of communication may make some difference with regard to the effect of university-based knowledge on firms and, hence, technical advance. Moreover, joint research centers provide vehicles for technology transfer that emphasize face-to-face interaction that may be more effective than other mechanisms for technology transfer. University-industry research centers also provide a vehicle for interacting with those technical personnel within industry that may be best able to exploit university research.

Industrial Perspectives on University-Industry Research Relationships

A full evaluation of the effectiveness of university-industry research centers, particularly their role in the innovation process, requires the perspective of industrial firms. Unfortunately, there have been few studies of industry perceptions of university-industry research centers based upon large samples of firms, and there does not exist a data source similar to our university-industry centers survey with which to examine the factors which influence industry participation in university-industry research centers. To address this issue, we first review a series of existing studies of this general subject and then turn to the results of our own focussed interviews on industrial perspectives on university-industry research relationships.

In addition to Blumenthal's studies, a 1995 study by Coopers and Lybrand explored industry's perspective on university-industry research relationships. While suffering from a number of methodological limitations, the study is useful because it examined the mechanisms through which a sample of some 424 so-called "growth companies" establish ties to universities and attempted to estimate the payback of those ties. The study found less than half of the companies in its sample had ties to universities. Of those that did, 70 percent hired student interns, 40 percent hired employees from the student population, and 44 percent used university faculty as resources. A significant share of companies in the sample had developed more formal ties to universities. Twenty-nine percent of companies with ties to universities were engaged in cooperative research and development, 20 percent made use of university laboratories and equipment, and 5 percent had licensed university science and technology. The study found that the companies in its sample that utilized university resources had 59 percent higher rates of "productivity," measured as revenue per employee, than those that did not, though this result should be interpreted cautiously since the study included no controls to account for other sources of this differential. The Coopers & Lybrand study found that slightly more than half (52 percent) of firms with relationships identified significant barriers that limited or hampered the effectiveness of the relationships. The major reasons included: a faculty culture that is not committed to business collaboration (18 percent), lack of active support in coordinating programs and resources for business (17 percent), a technology or research focus that is inappropriate for their business (14 percent), and lack of expertise in working with growing companies (13 percent).

A 1991 study by the Government-University-Industry Research Roundtable (GUIRR) and the Industrial Research Institute conducted detailed interviews with representatives of leading technology-intensive industrial firms on the factors that affect university-industry research relationships. The GUIRR-IRI study concluded that, from a corporate perspective, education and training are the most important functions of the university. Furthermore, universities play important roles for industrial innovation by providing a source of high quality talent and by functioning as central nodes in knowledge networks or "centers of thought." It found that while industry does not rely on universities for commercially viable innovations, universities can be sources of new knowledge required to improve existing technologies and develop new ones, although such knowledge is very far from commercialization. The study noted that university officials tend to have a narrow view of the innovation process, and to overstate the role and importance of academic research to innovation, believing that university-based science is the key source of major breakthroughs. Industrial participants suggested that universities should stick with basic research and not attempt to shift their research into extremely applied endeavors and product discovery and development for which they are ill-suited.

Most of the corporate participants in the GUIRR-IRI study expressed skepticism about the efficacy of university-industry research centers. The probability of a commercially viable product or process emerging from university-industry research centers was seen as "remote" at best. Centers were seen as well-suited to advancing the state of basic science and addressing generic issues in the development of new technologies, but as ineffective vehicles for achieving industrial innovation. Geographic proximity of participating companies and university-industry research was seen as an important contributor to effectiveness. A number of company officials noted that centers in which their own companies were engaged have yet to pay off in the development of commercial products, though such centers had generated new funds for university research efforts. One company official noted that his firm had dropped out of most university-industry research centers. Another company representative suggested that the value of joining a center is typically inversely proportional to the amount of knowledge a company has on a given subject. A representative from Monsanto noted that the company has yet to realize any demonstrated success from its major multimillion dollar alliances with Harvard and Washington University; as of 1991, no product leads had emerged from either project, a time-frame within in-house projects would either have led to such leads or been abandoned. Industrial affiliate programs at universities were viewed as particularly ineffective, and companies noted that they are less interested in participating; those that continue to do support such programs do so either as good will gestures or to gain access to students and faculty for recruitment.

Protecting intellectual property rights in joint university-industry research relationships was of major concern to industrial participants in the GUIRR-IRI study. Universities were seen as resistant to granting exclusive access to discoveries to firms who fund the work, and increasingly attempting to keep the rights to any intellectual property generated to themselves. Company representatives noted that universities are becoming more stringent in negotiating intellectual property rights for potential discoveries based upon the slim chance that a significant commercial breakthrough occurs. Furthermore, they saw a division of opinion on university campuses between university administrators who are adamant about claiming intellectual property rights and academic scientists who want to conduct research without burdensome policies.

As part of a 1995 study for the National Science Foundation, Dianne Rahm explored the ways that firms interact with universities. Although Rahm notes that this part of her study is based on a small number of cases and thus should be interpreted cautiously, her research indicates that firms perceive the ability to employ students, access to a scholarly library, a stable knowledge flow, input for corporate decision-making and tangible technology transfer as the main benefits from interactions with industry. The companies identified government policy as a powerful facilitator of university-industry research ties, both through federal granting agencies that drive universities and firms together and state economic development efforts that act as a booster for university assistance to firms. The firms in her sample noted both direct and opportunity costs associated with such relationships as the biggest obstacle to maintaining effective university-industry research relationships.

Rahm's detailed case studies based upon site visits to and numerous personal interviews at a number of firms in different industries identify four different models or types of firm interactions with universities. Large R&D intensive firms, according to Rahm, have myriad links to universities and support sponsored research at universities, affiliate with centers, employ university faculty as consultants, endow faculty chairs, and license university technologies. Such firms also take advantage of government programs that facilitate university-industry research ties. These firms understand that some fraction of university-industry research projects will not be successful and identify insufficient internal corporate capabilities to take advantage of university research as the main obstacle to more effective university-industry research relationships. Another group of large companies, particularly those which are downsizing, tend to use links to universities more strategically. Such firms focus on tangible and direct outputs, and tend to engage in sponsored university research in return for tangible outputs with well-defined intellectual property rights. A third group of companies are high-technology spin-off companies which have a personal relationship to universities. Such firms are dependent upon technology initially developed by a university, have close ties to the university, and often include a university faculty member among their founding group. The fourth group of companies are small and medium-size firms in traditional industries which see the university as a potential source of growth. These firms engage in opportunistic relationships with universities, often when federal and state money is available to subsidize these activities, and focus on projects with direct and tangible outputs.

We can get a fuller sense of the role of universities as a source of innovation by looking at the preliminary findings of a 1995 survey of the research and development activities of U.S. industrial companies conducted by one of the authors of this volume, Wesley Cohen, in collaboration with Richard Nelson and John Walsh.

[Floirda Note: COHEN-WALSH-NELSON DATA ON UNIVERSITIES AS SOURCE OF INNOVATION: TABLE (4-18 IF ADDED) AND BRIEF DISCUSSION TO GO HERE.]

Industry's Changing Views of Centers

We conducted interviews with R&D staff at a with a small sample of industrial firms to shed additional light on the perspective of industry. We selected firms of various sizes from five technology fields which were characterized by a relatively high proportion of university-industry research centers including two materials companies and one firm each in the biomedical, imaging, computer, chemical, pharmaceutical and telecommunications industries. Most of the firms were large R&D intensive companies. But, we did conduct interviews with two small-to-medium size companies in the materials and biomedical industries. The level of support for university research varied widely among firms - from $20 million to $1 million for large R&D intensive firms, and less than $1 million for smaller firms. Although the choice of firms in technology areas with high concentrations of university-industry research centers may introduce some selection bias into our findings, we felt it was important to orient such a focussed, labor-intensive inquiry in areas where there was potential high-payoff. We did not select firms based upon their prior involvement in university-industry centers.   We conducted interviews with senior technology managers at the corporate level, directors of central R&D laboratories, R&D managers, and scientific and technical personnel. These respondents possessed different levels of responsibility and different connections to universities. The interviews averaged one half to one hour in length and were conducted via telephone. The interviews followed a structured questionnaire format, although each interview included a significant amount of unstructured discussion. The findings of these company interviews while necessarily qualitative shed important light on industry's changing views of university-industry research relationships in general and UIRCs in particular.

First, almost every industry official we interviewed thinks that universities perform their traditional roles very well. Cutting-edge academic research is superb, and students are being well educated. Industry officials pointed out that university research was one of the great competitive advantages of the U.S. economy.

Second and related to this, the industry officials we interviewed reported that university research is important to their R&D efforts. According to our respondents, universities provide an important and to some extent irreplaceable source of long-range research and development, that is research with 5 to 10 year payoff periods. Such long-range research provides important benefits to firms by providing a window on new developments, pushing the "R&D envelope," and by suggesting new and at times fundamentally new ways of doing things.

Universities were consistently seen as the most important outside source of innovation, considerably more important that contract R&D firms or government laboratories for example. Universities provide an important source of outside knowledge, ideas and capabilities that are important to emerging technology and product areas. Respondents noted that in general they do not contract out routine work to universities of the sort that can be done in house or by consultants.

Most respondents noted that their firms look to universities to perform research in areas they are unable to cover internally. Many industry officials remarked that this situation had been exacerbated by cutbacks in corporate R&D, making their R&D units more dependent upon university research. This was particularly true in risky areas with substantial long-run scientific and commercial payoffs. Biotechnology firms were more likely to see universities as sources of more commercially-relevant knowledge. This is understandable since biotechnology is characterized by a close relationship between fundamental science and commercial application. Small firms were considerably more likely to depend upon universities for more applied and commercially relevant R&D. Part of the reason may stem from the more limited R&D resources possessed by smaller firms, and thus they may leverage university talent and facilities to a greater degree than their larger counterparts. One of the biomedical firms reported that university research is also used to validate its own research results to third parties.

The R&D managers we interviewed noted that university research provides access to qualified talent and new recruits at last to some degree. A majority of respondents did however point out that access to high quality students was not directly tied to their support of university research. Several respondents added that participation in industry-sponsored projects provides an important side benefit by exposing students to industrial problems and research styles, and at times helps to identify promising job candidates.

Third, the industry officials we interviewed said that corporate investments in university research are driven by a combination of fit, cost and quality. Firms pursue university research in areas with an important strategic fit to their in-house research program. This was true of both fundamental and more applied, or commercially relevant projects. Several firms noted that the decision whether or not to invest in university research is based in part whether it less expensive to support a university research team than to do the work in-house. One respondent pointed our however that universities may be starting to price themselves out of the market by raising overhead rates. A number of respondents also noted that universities may face increased pressure from outside competitors including universities in other countries, particularly the former Soviet

Union, and federal government laboratories which can offer high-quality research services at cheaper rates than leading U.S. universities.

All of the respondents pointed out that the most significant factor in funding university research is the quality and national reputation of the faculty member or research team. The reputation of the individual faculty member or team is far more important than that of the institution or department. Our respondents indicated that they support the "best person" in the field, regardless of the prestige of their home institution. Several industry officials indicated that they follow faculty members to different schools. A small number of respondents indicated that they try achieve geographic diversity in their university research support, funding leading faculty and research teams at various locations in the U.S. and abroad.

Fourth, despite the fact that they find university research useful an important, many of the firms we interviewed are reducing their funding of university research. A good deal of the explanation lies in more general cutbacks in industrial R&D. With the need to support and continue key internal R&D programs, R&D managers have fewer resources to support outside research efforts. One of our respondents reported that his company reduced its support of university research from a high of $12 million a year during the 1980s to just $1 million annually over the past several years. While industrial R&D managers would like to increase support to university research and to industrial R&D more generally, they must compete for resources with more powerful corporate units. The R&D manager of one firm attempted to increase university research support from 5 to 10 percent of the firm's total R&D spending on academic research, but this effort was vetoed by the company's board of directors. However, one firm has significantly increased its support of university research. This firm has also implemented a formal and systematic process by which requests from universities are internally reviewed on a "merit basis."

Fifth, the R&D managers we interviewed are frustrated with a number of aspects of its interactions with universities. These include differences in culture and attitudes and the different time-scales on which academic and industrial researchers tend to work. Many respondents complained that universities are stodgy bureaucracies. As one respondent put it: "universities do not want to change." Most respondents believe that faculty differ markedly in their desire and ability to work with industry, noting that they try to find faculty they feel understand industry. At least one R&D manager we interviewed felt that attitude of faculty toward working with industry had improved remarkably over the last five years. A number of respondents recommended more interaction at the bench scientist level and less at the senior corporate executive-academic administrator level, reminiscent of our results above regarding technology transfer effectiveness.

The biggest source of tension involves intellectual property issues. Nearly every industry officials we interviewed reported that they are increasingly frustrated by their dealing with university intellectual property offices. Industry is at odds with the policy of most universities retaining ownership of intellectual property generated by industry-funded research projects. Companies want to own the rights to results from research they fund. The industry officials we interviewed complained that the universities have established intellectual property or licensing offices staffed with lawyers that interfere considerably with interaction between university researchers and the companies. While respondents pointed out that the most prestigious universities are typically the hardest to negotiate with, this is a problem that affects virtually all university-industry relationships. The industry officials we interviewed noted a few instances when a university's insistence on retaining control over intellectual property caused the collapse of an ongoing university-industry research relationship. Virtually all of the industry officials we interviewed believed that university-industry cooperation could be improved if both sides acknowledged and agreed upon up-front what was going to be done over the course of the industry funded research program.

It is worth pointing out that none of the industry officials we interviewed indicated that they were concerned that their participation in university research or in UIRCs would results in the compromise of proprietary information to competitors. Firms were not particularly worried about foreign companies participating in joint research with U.S. universities. In their view, the biggest sources of technology transfer occurs through foreign students who take positions with firms in their home countries. As one respondent put it: as long as universities are going to educate foreign nationals, they might as well "take the foreign companies' money" to do useful research.

Sixth, industry is generally disenchanted with large research centers, and feels that it can more efficiently obtain useable research results out of one-on-one interactions with professors. Industry prefers modest project grants to a professor or research team, rather than participate in larger university-industry centers. Several respondents explicitly noted that they prefer to make research multi-year grants on the order of $50,000-$100,000 in total support. Industry officials reinforced the view outlined in Chapters 2 an 3 that centers are the product of university initiative and government, and are not the mode of interaction favored by industry.

Firms are eliminating "philanthropic" funding of university research, and are becoming more strategic in their funding of university research, particularly as their own R&D laboratories face cutbacks. Faced with increasing pressure to achieve results, company research divisions are resorting to smaller contracts with single faculty that last several years. Reflecting this shift, university research projects are increasingly initiated, funded and managed by group level R&D managers who pay for these projects out of their own budgets and not out of corporate funds. One company completely abandoned a long-standing policy of providing unrestricted research support to universities in favor of this type of strategic arrangement which offers a greater degree of control.

Industry officials described a series of problems with large research centers. Principally, the results are often not directly relevant to the interests of the participating company. Centers are organized around a set of research projects which by definition must appeal to a large number of firms. The consequence is that these projects are very general and thus of less specific relevance or value to any one firm. Furthermore, companies also feel that centers are difficult to control. With many participants it is hard for any one company to influence the research agenda or extract intellectual property from center research. A number of industry officials we interviewed perceive centers as vehicles providing little more than "philanthropic" support for university research. Others were more cynical, viewing them as ways to take industry's resources and do what they like. They suggested that universities form centers to attract industrial and government funds, but that relationships with firms are sometimes ignored after the corporate money is secured. In fact, a number of executives indicated that centers are often centers in name alone, and used by universities to attract money. One vice-president for research summarized his view by stating: "The university takes this money, then guts the relationship."

The R&D managers we interviewed also believe that the role of centers in promoting interdisciplinary research is more hype than reality--the exceptions being leading centers at Stanford, Berkeley, Carnegie Mellon and MIT. From their perspective, centers are typically interdisciplinary "in name only." One respondent pointed out that "interdisciplinary" centers have been useful to industry not because centers have managed to successfully integrate faculty across disciplines, but because some individual faculty that have successfully made their individual research successfully interdisciplinary. Regardless of how successful centers have been at interdisciplinary research, many firms indicated that they are very interested in this type of research from universities.

One-to-one relationships provide considerably more flexibility and control over research activities and intellectual property. Companies can identify faculty members or research teams with which they share common interests and working styles, and are able to fund research in which they are directly interested. One-on-one relationships also allow for university and company researchers to cooperate on real problems, as opposed to the situation where the company contact for a university research project only very minimally pays attention to a center's activities. There is a higher probability that a level of applied research and disclosure restrictions can be found that is acceptable to both the firm and the academic researcher. They also push the locus of interaction down to the level of the actual researcher where the work is actually done rather than the administrative level. One-on-one relationships provide the flexibility for both industry and faculty to maximize their respective objectives.

Notwithstanding these benefits to one-on-one relationships, a number of benefits of centers were noted. Centers are a good vehicle for keeping abreast of important emerging research. Since the costs of monitoring all the work in a given area can be high, centers can often provide a good mechanism for collecting information and making it accessible. According to the industry officials we interviewed, this benefit is probably worth the cost of lower "associate" memberships available in many centers. Respondents also noted that centers are also useful vehicles for conducting "pre-competitive" research of the sort done by industry consortia. Interestingly, the one firm preferred centers as a mode of university-industry interaction, noting that it would like all the university research it funds to be done in centers. This company noted that it prefers that the standard intellectual property policy of the centers of which it is a member have eliminated hassles over intellectual property. Another respondent suggested that centers be might structured along a one-firm-many-universities mode rather than a one-university-many-firms mode to make them more relevant to industry needs and minimize difficulties associated with intellectual property.

Somewhat contrary to the views of many industry executives reported above regarding their interest in downstream research, industry is concerned that UIRCs are leading universities to redirect their research from the pursuit of fundamental science into more applied areas. Virtually all of the respondents expressed considerable concern that the trend toward university-industry research relationships in general and UIRCs might be causing universities to redirect their research activities from long-range basic science toward more applied or downstream endeavors.

Finally, industry expressed mixed feelings and a number of concerns about government funding. On the one hand, several industry officials noted that their ability to leverage government research funding to universities makes their investment in university research more economically beneficial. Firms were particularly enthusiastic with the various university-industry research center programs funded and managed by the National Science Foundation. On the other hand, a number of respondents were concerned that government R&D programs, such as those which encourage and support university-industry research centers, tended to contribute to this shift to more applied work. Still, others were worried that proposed cutbacks in federal support for university research might make universities increasingly dependent upon industrial funds, causing them to redirect their activities toward more applied endeavors.

In this chapter, we have considered the effects of university-industry research centers on the generation of various forms of scientific and innovative output, and have examined the ways that such centers effect the process of industrial innovation. But, there is yet another way that university-industry research centers affect the process of technological change. Simply put, this involves the implications that ties to industry pose for the university's research mission and academic science in general. It is to this issue that we not turn.

Chapter 5

Eminence and Enterprise:

Challenges for Academic Science.

Industry is generally inhibited by preconceived goals, by its own clearly defined standards, and by the constant pressure of commercial necessity. Satisfactory progress in basic science seldom occurs under conditions prevailing in the normal industrial laboratory. There are notable exceptions, it is true, but even in such cases it is rarely possible to match the universities in respect to freedom which is so important to scientific discovery (Vannevar Bush, *Science: The Endless Frontier*, 1945, p. 19).

The institutional conception of science as part of the public domain is linked with the imperative for communication of findings. Secrecy is the antithesis of the norm; full and open communication its enactment. The pressure for diffusion of results is reenforced by the institutional goal of advancing the boundaries of knowledge and by the incentive of recognition which is, of course, contingent on publication (Robert Merton, "The Normative Structure of Science," 1942).

There is no more contentious issue surrounding university-industry research relationships than the implications they pose for academic science. A growing number of commentators contend that increasing industrial funding is inducing a shift from basic to more applied research, consuming the seed corn of the American science and technology enterprises. Some have argued that joint centers between university and industry pose a fundamental challenge to the basic tenets and norms that have governed so called *open* academic science over the centuries. There is concern that greater involvement with industry and increased emphasis on commercial concerns will corrupt academic research and potentially destroy the free and open communication that is the hallmark of academic science. Others fear that corporate concerns for the protection of intellectual property may at times outweigh the ability to freely publish the findings of scientific research, and lead to the imposition of publication delays, or, even worse, to the selective suppression of the public disclosure of the findings of scientific research.

In this chapter, we focus on the implications that deepening university-industry research relationships pose for academic science and for the university more broadly. We provide detailed data from our survey of university-industry research centers on industry's ability to influence the research agenda, to restrict communication and information disclosure, and to delay the publication of university research findings and have findings deleted from university research. We also explore the types of intellectual property university-industry research centers grant to industrial participants and the effect of various intellectual property regimes, and research activities more generally, on the performance and productivity of centers. At bottom, we argue that industrial funding of and participation in university research pose an important tradeoff for university researchers and society--between the traditional norms that govern academic science and the pursuit of technology of more immediate and direct relevance to industry.

The Imperatives of Science

Some fifty years ago, Robert Merton posed his classic distinction between the quest for being first to discover (or what he referred to as "priority" in discovery) as the underlying motivating force for academic science and the profit-orientation of industrial research. In an article published in 1938, Merton argued for the autonomy of science, writing that:

> Science must not suffer itself to become the handmaiden of theology or economy or state. The function of this sentiment is to preserve the autonomy of science. For if such extra-scientific criteria of the value of science as presumable consonance with religious doctrines or economic utility or political appropriateness are adopted, science becomes acceptable only insofar as it meets these criteria. In other words, as pure science sentiment is eliminated, science becomes subject to the direct control of other institutional agencies and its place in society become increasingly uncertain.

In his seminal 1943 article on the normative structure of science, Merton elaborated on the relationships between science and the broader social structure, arguing the goal of science is to add to the stock of knowledge in the public domain. In particular, he argued that the ethos of science revolved around four institutional imperatives: universalism, communism, disinterestedness, and organized skepticism. Universalism essentially means that scientific contributions are judged by impersonal, objective criteria. Communism refers to the public nature of scientific knowledge--the common ownership of the fruits of science--which are to be shared and not kept secret. Disinterestedness refers to the pursuit of knowledge for its own end, and to the benefit of the broader scientific community and the general public as opposed to individual or corporate gain. Organized skepticism means that the judgement of scientific work turns on the detached scrutiny and peer review of data and evidence. For Merton, the reward structure of science revolves around the concept of priority of discovery which in turn presupposes free and open disclosure. These imperatives sharply distinguish academic science from the profit-motive, proprietary impulses, and secrecy associated with the pursuit of technology for commercial ends. In his words:

> The substantive findings of science are a product of social collaboration and are assigned to the community. They constitute a common heritage in which the equity of the individual producer is severely limited. ... Property rights in science are whittled down to a bare minimum by the rationale of the scientific ethic. The scientists claim to "his"

> intellectual "property" is limited to that of recognition and esteem which, if the institution functions with a modicum of efficiency is roughly commensurate with the increments brought to the common fund of knowledge. ... Given such institutional emphasis on recognition and esteem as sole property right of the scientists in his discoveries, the concern over priority becomes a "normal" response.

Building on the classic work of Merton, Partha Dasgupta and Paul David suggest that there is a profound gulf between the communities of "open science" and "proprietary research," the former being organized around augmenting the stock of public knowledge, while the latter generate private knowledge which can be appropriated by sponsoring organizations. Like Merton, they note that the distinction between these two modes of knowledge production turns on the respective goals they pursue, the norms and policies that govern disclosure of knowledge, and the nature of the reward and incentive systems under which scientists work. An implication of these authors' writings is that industry-supported university researchers may not be able to manage the tension that might arise from the different objectives and incentives of academia (science) and industry. Dasgupta and David further caution that as university research becomes more closely tied to industry's drive to commercialize technology, industry's profit motive may displace the incentive of priority that has traditionally motivated university researchers. In the process, the norms of public disclosure that govern university research and especially the pursuit of basic scientific research may be undermined. In their view, such a process may generate significant social costs by consuming the “seed corn” that spawns technological advance in the long run. Thus, deepening ties between university and industry may not only compromise some of the fundamental tenets of academic research in the short run, but they may impose longer run social welfare costs in the form of a diminished rate of technical advance. They summarize their view in terms of four key propositions.

> (1) Although the institutions and social norms governing the conduct of open science cannot be expected to yield an optimal allocation of research efforts, they are functionally quite well suited to the goal of maximizing the long run growth of the stock of knowledge--subject to the constraints on the resources that society at large is prepared to make available for that purpose.
>
> (2) Those same institutions and social norms, however, are most ill-suited to securing a maximal flow of economic rents from the existing stock of scientific knowledge by commercially exploiting its potential for technological implementations. The distinctively different set of institutional arrangements, and different modes of conduct on the part of researchers, that accordingly have been contrived for the latter (technological) purposes unfortunately leaves unresolved the problems of securing the right amount of resources for the conduct of *open* science. Here, adequate public

patronage is critical and warranted.

(3) The organization of research under the distinct rules and reward system governing university scientists, on the one hand, and industry scientists and engineers, on the other, historically has permitted the evolution of symbiotic relationships between those engaged in advancing science and those engaged in advancing technology. In the modern era, each community of knowledge seekers, and society at large, has benefitted enormously thereby.

(4) The institutional machinery which has been performing these vital functions for our society is intricate, jerry-built in some parts, and possibly more fragile an sensitive to reductions in the level of funding for open science that often may be supposed. For all their importance to the modern economy and polity, the social mechanisms that allocate resources within the Republic of Science are still too little understood, and remain vulnerable to destabilizing and potentially damaging experiments undertaken too casually in the pursuit of faster national economic growth or greater military security.

Despite their claims to a "new economics of science," Dasgupta and David's views are far from unanimous, even among economists. Although Dasgupta and David appropriately focus attention on the social costs of close ties between industry and universities, others suggest that the complex and interactive character of the innovation process may mitigate such costs in the long run. In their studies of the historical relationships between university and industry Nathan Rosenberg and Richard Nelson argue that efforts to advance commercial technology often stimulate basic research as bottlenecks and opportunities for basic science are inevitably encountered. Thus, it follows that an immediate shift in resources away from basic research need not undermine basic science in the long run.

The 1994 survey of industrial participants in the life sciences industry by David Blumenthal and his collaborators, however, provides evidence that industry is indeed subverting traditional academic norms. The findings from this study are particularly interesting in that his survey asked industrial firms about their policies and experience with policies toward academic secrecy, confidential information, and the ability to delay publication. Blumenthal found that a substantial majority of companies (82 percent) which supported academic research in the life sciences reported that they sometimes require academic researchers "to keep information confidential to allow filing of a patent application." Importantly though, nearly half of respondents (47 percent) reported that they have occasionally required universities to protect confidential and proprietary information longer than it takes to file a patent. Fifty-six percent of respondents reported that academic research often or sometimes results in information that is kept confidential longer than it takes to file a patent, and 58 percent reported that they typically require academic researchers to keep information confidential for more than six months in order to file a patent application, considerably longer than the NIH guidelines of 30-60 days.

While our survey data cannot directly address either Dasgupta and David’s or Rosenberg and Nelson’s conjectures about the long run effects of deepening ties between university research and industry, the survey data do allow us to consider the short run implications of university-industry research centers for the public disclosure of research, the free flow of ideas in academia, industry's ability to influence and shape the agenda of university research, and the immediate influence on technical advance of the more "commercial" activities conducted in such centers.

Industry Influence on Academic Research

To what extent does industry influence or control the research agendas of university-industry research centers? What are the dimensions of industry control - how does it manifest itself? What challenges does industrial research funding and industry influence over the research agenda of centers pose for academic science?

An important issue is the ability of participant firms to influence the research agenda of the research centers. According to Merton's emphasis on open science and long held university traditions, academic science has been essentially priority-driven research, in which individual scientists or teams of investigators determine what problems to investigate based upon developments outlined in the broad body of scientific knowledge and the scientific literature. According to Merton and others, this process of making cumulative additions to the stock of knowledge moves science forward in a useful and efficient manner. Thus, the extent to which individuals and institutions other than academic scientists influence and set the research agenda would represent a fundamental challenge to the traditional tenets undergirding academic science. This is not to say that science is never guided by social needs and priorities. As Chapter 2 has shown, academic science has been informed and shaped by government military and social needs for quite some time, most certainly in the period after world war II when government became a leading patron of science. Still, as we have seen, scientists have for the most part have been able to set their own research specific agendas in the context of those social needs and priorities.

The findings of our survey research indicate that industry has had significant influence over the research agendas of the university-industry research centers in our sample (see Table 5-1). On a four-point Likert scale where response categories ranged from "no influence" to "strong influence," the responses indicate there is significant company influence on the research agenda of research centers. Nearly two-thirds (64.5 percent) of respondents indicated that participating companies had moderate or strong influence over their research agenda. At the same time, however, survey respondents report that industry has little or no influence over their fiscal management or operating procedures.

[Table 5-1 about here]

Restricting Information Disclosure

Traditionally, the results of university research have been regarded as a public good, and universities have strongly subscribed to the norm of the free flow of ideas. Indeed, for Merton and for many others, free and open information disclosure lies at the very heart of the pursuit of pure academic science. According to this view, free and open disclosure of findings, the process of reporting and debating findings, and the process of critical peer review and evaluation contribute fundamentally to the process of scientific advance and discovery.

Again, the findings of our survey research indicate that university-industry research centers appear to be compromising these traditional features of university research. Table 5-2 shows that participating firms were allowed to restrict communication and information flow both inside and outside of these research centers. Not surprisingly, participating companies restricted the flow of information to other companies. Perhaps more significantly, the center directors responding to our survey indicated that the faculty and staff associated with the center are sometimes restricted in sharing information about the center projects on which they work. Here, 13.4 percent of survey respondents indicated that sharing of information related to particular projects is at times restricted among faculty within the center itself. In addition, 21.3 percent reported that information sharing is at times restricted between faculty affiliated with the center and other scientists and professors within the same university. Almost twenty-nine percent of respondents reported that communication is restricted between faculty in the center and professors at other universities. Furthermore, 41.5 percent of centers reported that there are restrictions on information sharing between the center and the general public.

[Table 5-2 about here]

Some commentators have suggested that restrictions on the disclosure of scientific information by university faculty are nothing new, given the imposition of such restrictions on classified national security research during the Cold War. But, as Chapter 2 has shown, classified research typically occurred in specialized institutional settings (e.g. national laboratories and contract research operations managed by universities) which were separate from the universities proper. At least one university, Harvard University, was sufficiently concerned about the problems associated with the imposition of such restrictions that it prohibited classified research on its campus. Furthermore, as was also discussed in Chapter 2, while organizations engaged in classified national security research were closed off from the outside world and did place strict restrictions on communication and information flow between their research staff and the general public, there tended to be open information flows and communication within such organizations. In contrast, university-industry research centers are characterized by a new and potentially even more vexing type of information restriction--the inability of industry-funded scientists in the same center or same academic department to share their research results with one another. More importantly, however, defense related work performed at universities is a form of *public* good, while information and communication restrictions placed on research activities funded by firms contribute directly to the *private* benefit of these companies.

Publication Restrictions

A related issue involves the ability of participant firms to affect the publication of information and in some case of scientific information either by imposing a delay or requiring information to be deleted from research papers before submission for publication. The sociologist, Merton, took a strong position on this issue, considering full and complete publication of the findings of scientific activity to be an unassailable tenet of academic science. In fact, in his writings he criticized those scientists who chose not to publish their findings in a timely fashion, even when they were unsure or insecure about their findings, on the grounds that such acts were selfish and held back the cumulative advance of science. Here, Merton believed that even if new theories and findings ultimately proved to be inaccurate or even wrong, it was necessary to publish them in the open literature so that they could be subject to the sort of critique and vetting that would ultimately lead to scientific advance.

As Table 5-3 shows, university-industry research centers have violated the norm of complete and timely publication in two ways: by imposing delays on publication of research findings and by requiring that specific findings be deleted from published reports. More than a third of the centers in our sample reported that participating companies are able to require information to be deleted from research papers before submission for publication. More than half (52.5 percent) reported that participating companies are able to delay the publication of research findings. Almost one-third of centers (31.1 percent) reported that participating companies are able to both delay publication and have information deleted from research papers and reports. Furthermore, we found a strong positive relationship between the level of industry support and data deletion. Fully half of centers that obtain more than 50 percent of their support from industry reported that participating firms have the ability to require data deletion, compared to 30 percent of centers which depend upon industry for less than 50 percent of their support. It is important to remember that our survey asked center directors to report whether participating companies *can* delay publication or require that information be deleted. Our data do not indicate the actual frequency with which publication is delayed or information deleted. Furthermore, our survey data do not indicate what kind of information companies can require to be deleted, as our question simply asked whether information can be deleted, as opposed to scientific findings.

[Table 5-3 about here]

Not surprisingly, the extent of industry's influence over publication varies with the degree of importance the center attaches to the goal of improving industry's products or processes. Centers that hold this goal as very important were more than twice as likely to permit participating firms to have information deleted, and more than 50 percent more likely to allow firms to delay publication compared to centers for which this goal is unimportant.

Intellectual Property

The granting of intellectual property to private firms is another issue that has generated significant controversy. In fact, according to Merton, the very act of granting intellectual property is a perversion of the traditional norms undergirding academic science. Slightly more than half of the centers in our sample (52.8 percent) granted intellectual property rights of one form or another to companies that funded their research. As Table 5-4 shows, 45.8 percent granted licenses, 26.0 percent granted exclusive licenses, 26.0 percent assigned patents to industry, and 14.5 percent granted copyrights. Thus, many a significant fraction of university-industry research centers appear willing to grant proprietary rights over intellectual property to participating companies. Furthermore, the granting of intellectual property is associated with the level of industry support. More than 40 percent (43.0 percent) of centers which obtained over 50 percent of their total support from industry granted intellectual property to participating companies compared to 36.6 percent of centers with less than 50 percent of their support from industry.

An important question is whether those centers that see their primary mission as improving industry's products and processes to be more likely to confer intellectual property rights than centers that have a more academic orientation. As Table 5-4 shows, the survey data suggest that this is indeed the case. The willingness of centers to grant such property rights clearly increases with the degree of importance centers attach to a commercial mission. The granting of patents and exclusive licenses show the sharpest trend, increasing by about 25 percent (in absolute terms) along this dimension. Recall from Chapter 3 (Table 3-9) that the increase in the importance of this mission within UIRCs is also associated with a dramatic decrease in the share of center R&D activity that is basic research and an increase therefore in the share that is applied research and development. These results provide further evidence that closer association on the part of academic researchers with industry lead to less traditionally academic activity, as predicted by Dasgupta and David.

[Table 5-4 about here]

We also examined the intellectual property policies of centers in the eight key technology areas -- again those areas are advanced materials, biomedical, biotechnology, computer software, advanced manufacturing, environmental technology, computer hardware, and semiconductors). As Table 5-5 shows, this results of that analysis indicate that more than a quarter of centers in every field granted exclusive licenses and patents to participating companies. Centers in biotechnology (40 percent), semiconductors (39 percent), computer hardware (36 percent), and environmental technology (34 percent) were the most likely to grant exclusive licenses to their industrial sponsors, while centers in computer hardware (44 percent), advanced manufacturing

(39 percent), and advanced materials (38 percent) were the most likely to grant patents.

[Table 5-5 about here]

Academic Science, Commercial Technology: Terms of the Tradeoff

As we have already seen, many students of university-industry research relationships take a pessimistic view, arguing that such ties necessarily damage the university's research mission, by encouraging a more applied research focus among academic researchers and damaging the university's culture of free and open discussion of research findings. Others take a more optimistic view of the research relationships between university and industry. They see such relationships as leading both to new ideas and innovations emerging through cooperative efforts and more importantly to turn them into successful commercial products. We hope that the arguments and analysis in this book will show that while there is some merit in both of these positions, each represents an over-simplified and to some degree one-sided view of the nature of the research relationship between the universities and industry.

A central premise of this book is that the relationship between university and industry is complex and nuanced. In our view, the way that industry funding affects the nature of academic research can be best conceptualized in terms of a tradeoff. Put at its simplest, the nature of this tradeoff suggests that to the extent that universities seek to contribute to industrially-relevant research and to technical advance of a commercial nature, they may have to relinquish some of the norms and tenets of free and open scientific inquiry that have for so long informed academic science. While this may come at the cost of advances in basic science, it will in turn generate benefits of a more immediate and commercially-relevant nature. Basically, we suggest that universities may compromise on traditional academic norms both to attract greater industrial support, and in doing so generate more commercially relevant technology, but perhaps less academic science.

Furthermore, we conceptualize the tradeoff as having two components. The first is the tradeoff which faces the university specifically. This is a tradeoff between the unfettered pursuit of academic or scientific eminence and the need to generate research resources. The tradeoff here is that generating resources from industrial sources may require that university faculty and researchers give up some degree of control of their research agendas and some of their long-held academic autonomy to attract resources from industry. This tradeoff, which is faced primarily by university faculty and administrators, ultimately poses a larger and more consequential tradeoff for society. The essence of that tradeoff is between discoveries with large potential benefits for economic and social welfare in the future and the desire to generate commercially-relevant technology in the near-term. The main element of this tradeoff for society, in our view, does not lie in the fact that industrial support of academic research may lead to more applied research as opposed to basic research, as others such as Paul David and Partha Dasgupta have so eloquently argued. Our position is more in line with that of Merton and is grounded in the notion that open disclosure is central to the most efficient pursuit of science. At bottom, we worry that the imposition of restrictions on the disclosure of scientific findings, while it may lead to more rapid achievement of technical advance in the short run, may impede more basic scientific progress which is so important in the long run. Put another way, the central element of the tradeoff lies in the fact that disclosure restrictions, of the sort that are often required to attract industrial sponsorship, tend to hinder and impede the cumulative advance and building process which is so crucial to scientific progress and thus undermining or at the very least postponing the social and economic improvements that such scientific progress brings.

There is no doubt that universities and university researchers derive clear and substantial benefits from their interactions with industry. The most obvious of these is financial support for research. More than nine in ten of the centers in our sample (91.3 percent) of centers report such financial report this as a benefit of their interactions with industry,a s table 5-6 shows. In addition, more than two-thirds (68.1 percent) of centers reported that they received equipment from industry and another 44.8 percent indicated that access to industrial facilities and data was obtained from interacting with industry. This is not to say that attracting direct and in-kind support is the only reason university researchers seek industry cooperation. A large share of the centers in our survey also reported that the ability to interact with industry was important in itself, with 69.7 percent of centers viewing the “opportunity to confer with industry” as important, and more than half (55.8 percent) indicated that obtaining “information on industry needs" was important, as table 5-6 also shows.

[Table 5-6 about here]

To probe the nature of the tradeoff between academic science and commercial technology more directly, we examined the differential effects of both intellectual property and information disclosure policies on both the academic and commercial performance of university-industry research centers (see the discussion of commercial and academic performance in Chapter 4). To do so, we looked at three related questions. First, how does the granting of intellectual property affect both the academic and commercial performance of centers? Second, how does that granting of disclosure restrictions affect center performance? And, third, how does the allocation of research effort affect center performance? On the one hand, we suspected that centers which had policies which reflected a more traditional academic mission, that is centers which vigorously pursue basic research, do not allow disclosure restrictions and/or do not grant strong forms of intellectual property to industry, would have higher rates of academic productivity, such as the production of academic papers and articles. On the other hand, we suspected that centers which conducted more applied research and which were more likely to engage in disclosure restriction and grant substantial intellectual property to industry would be more likely to generate higher rates of commercial output and productivity. And, as we will see, this is basically what we found. Consider the following.

We began our examination of this issue by exploring the effects of intellectual property polices on both the academic and commercial performance of centers. We defined intellectual property as those policies that give industry patent rights or exclusive licenses to center generated intellectual property. To start, we divided our sample in two groups and compared the academic and commercial productivity of centers which have conferred intellectual property to industry and those that did not. As Table 5-7 shows, centers which granted intellectual property to participating companies generated anywhere from two to three times the rate of commercially relevant outputs than those which did not. But, the granting of intellectual property in this way had a negative effect on academic productivity, being associated with a 10 percent decrease in the production of academic research papers. Intellectual property was also associated with a reduction in the production of graduate students. Furthermore, centers which granted intellectual property were more likely to report that "improving industry's products and processes" was a central goal. To gain further insight on this issue, we examined how intellectual policies affect center performance for each of the 17 technology fields in our sample. **[Wes, these analyses are two-way table analyses like the aggregate ones in the book, not regressions. Do you want me to verify these results by doing regressions for all outputs for all technology areas? Note, that's almost 900 regressions for this chapter].** Generally speaking, we found that centers which provided stronger intellectual property protection also achieved higher rates of productivity for the industrially-relevant outputs and lower rates of paper production as well as lower rates of intermediate outcomes.[1] The exceptions were the fields of biotechnology, biomedical, robotics, instruments, energy, environmental technology, agriculture, and so-called "other" areas. Furthermore, the production of research papers tended to rise with intellectual property restrictions in the fields of biomedical, robotics, energy, environmental technology and "other" areas. We believe that this result is at least in part related to the relative closeness between academic science and commercial technology in these fields. Finally, we conducted regression analyses designed to gain a more fine grained sense of this relationship. The findings from these regression analyses indicate that the granting of intellectual property to companies is associated with increases in commercial-relevant outputs such as invention disclosures, prototypes, new products, and new processes.[2] Basically, the combined results of these analyses support the notion of a tradeoff, centers which grant more intellectual property to industry generate more commercial innovations but (in all but a few special cases) sacrifice academic outputs.

[Table 5-7 about here]

---

[1] It is worth pointing out that the results for educational outputs were somewhat anomalous. Centers which granted intellectual property tended to produce more Ph.Ds, while centers which were less likely to grant intellectual property produced more masters' degrees.

[2] It is also worthwhile to report that centers that grant patents or exclusive licenses to industry are *less* productive in the generation of intermediate outcomes than those that do not. However, the regression analyses again indicate statistically significant differences in UIRC intermediate productivity production between centers that do provide intellectual property and those that do not, with those that do exhibiting greater productivity.

To gain additional insight into the nature of the tradeoff between academic norms, commercial technology and scientific advance, we looked at the ways that information disclosure restrictions, in particular the deletion of information or findings from papers and publications, might effect the commercial and academic output of centers. We began by examining the productivity levels of centers which allow data deletion and those which did not. As Table 5-8 shows, centers which allow data deletion were considerably more productive in terms of commercial outputs, similar to the result for intellectual property. Furthermore, centers which allow data deletion had lower rates of academic or paper productivity. These centers were also likely to rate the goal of improving industry's products and processes more highly than others. Again, we did this analysis for each of the seventeen technology fields. The results here conform to the overall pattern: Disclosure restrictions were associated with greater commercial productivity and lower rates of academic output. The only exceptions to this pattern were biotechnology, agriculture and telecommunications where research paper productivity did not decline as a result of disclosure restrictions. Finally, we did regression analyses to control for other factors that may affect productivity, the results of which provide additional evidence of the tradeoff showing that disclosure restrictions were positively associated with the production of prototypes and new products and with intermediate outcomes, and negatively associated with and the production of academic papers and Ph.Ds.

[Tables 5-8 and 5-9 about here]

A third way we examined this tradeoff was to explore how the allocation of research effort (in particular a high level of basic research) affects the commercial and academic performance of centers. Once again, we began by dividing the sample in two and doing a simple comparison of centers that devote less than 50 percent of total center effort to basic research and centers that devote 50 percent or more of total effort to basic research. Not surprisingly, we found that centers which devoted more of their effort to basic research generated higher levels of papers and graduate students. These centers also tended to generate higher levels of patent applications and patents. They were much less likely, however, to generate new products, new processes and new prototypes. We also found that centers which seek to "improve industry's products and processes" were less likely to engage in high levels of basic research: Centers that consider this goal as more important conducted less basic research and were less academically productive, though more commercially productive, than other centers. We replicated this analysis for the 17 specific technology fields. Here, we found that higher levels of basic research tended to be associated with greater academic outputs, but lower levels of commercial outputs. The only exceptions to this were the fields of transportation and agriculture. We conducted regression analyses to probe the effects of level of basic research on the academic and commercial performance of centers. The results here lend additional support to our formulation of the tradeoff, indicating that basic research is very strongly positively associated with greater research paper and Ph.D. productivity, negatively associated with prototype production, and strongly negatively associated with the production of the sorts of intermediate outputs discussed in Chapter 4.

[Table 5-10 about here]

The Offsetting Role of Quality

So far, we have explored the tradeoff between academic norms and the quest for scientific versus commercial outputs, and we have found significant support for the view that our formulation of this tradeoff. University-industry research centers which seek to achieve commercial advance and take on the mission of "improving industry's products and processes" were found to be more likely to relinquish their commitment to the traditional academic norms regarding intellectual property or disclosure restrictions. While these centers did tend to realize greater commercial innovation as a result, they did so at the cost of academic output. There is another class of centers, however, that appear to be more academically-oriented, which are less likely to confer intellectual property to industry or to restrict disclosure and more likely to invest in basic research. These centers were found to produce a high level of academic output, but significantly lower levels of commercial output. These, then, are the terms of the tradeoff we have explored thus far.

But, there is at least one other factor that can affect the terms of this tradeoff. As anyone who is familiar with the academic world can attest, a great deal of what goes on the academic community is driven by prestige, reputation and the perception of quality. In fact, the organizational sociologist, Arthur Stinchcome, echoing Robert Merton's seminal formulation to some degree, refers to academic organizations as being virtually defined by "reputational labor markets." Thus, it is important to ask the extent to which reputation or "quality" of an academic organization or center might offset or alter the terms of the tradeoff between academic norms and academic versus commercial performance. In our view, it is likely that academic organizations or centers with prestigious reputations and high quality rankings will be much more likely to withstand or offset industry pressures for greater control, higher levels of intellectual property and greater information disclosure. In part, this is due to the fact that highly ranked researchers and organizations would be more likely to be able to raise research resources from many sources including key government sources such as the National Institutes of Health, Department of Defense, and National Science Foundation, and as such be far less dependent upon industry as a source of research resources. To help us understand this issue, we examined the effects that the academic quality of university-industry research center faculty has on both their productivity and their activity.

There are any of a number of ways to define and to measure "academic quality." But, for our purposes here, we used the 1995 evaluations of academic quality by the National Research Council and the National Academy of Sciences. These evaluations were extremely comprehensive in that they covered 3634 doctoral granting departments in 41 disciplines at 274

American universities. The evaluations were designed to rate the "scholarly quality of the program faculty" and were based upon surveys of a minimum of 200 faculty in each disciplinary or program area. In short, these evaluations provide useful, comprehensive and reliable *reputational* measures of academic quality.

To begin, we divided the centers in our sample into quality groups, essentially quartiles, according to academic quality. We then examined the academic and commercial productivity of centers in these quality groups. Table 5-11 shows the examines productivity in dollar terms and Table 5-12 in terms of personnel. As Table 5-12 shows, academic quality was strongly and positively associated with academic research productivity, in other words with the production of papers and Ph.Ds. However, there was little or no association between academic quality and many measures of commercial performance, such as invention disclosures, patent applications, patents. In fact, academic quality tended to be negatively associated with the production of the most downstream outputs, new products, new processes and prototypes, as well as master's degrees. We ran regression analyses to further explore the effects of academic quality on performance, controlling for other factors, the results of which provided further evidence that quality was associated with improved research paper and Ph.D. production and had no statistically significant effect on the other outputs, with a significant negative effect for products.[3]

[Tables 5-11 and 5-12 about here]

The next step in our analysis was probe the issue of the offsetting role of quality more directly: that is, to look at the effects of academic quality on the on the propensity of centers to grant intellectual property to industry and restrict information disclosure. Our analysis was framed by the conjecture that higher levels of quality would enable researchers to more effectively offset or resist restrictions and reinforce traditional academic norms. The analysis confirms this conjecture. For example, the number and percentage of centers that grant industry intellectual property or allow information to be deleted from center publications declined steadily with quality, as Table 13 shows. The highest ranked centers were the least likely to engage in either departures from traditional academic norms regarding open disclosure and public intellectual property. Furthermore, the level of effort devoted to basic research increased with quality. Regression analyses revealed that academic quality was the *principal* determinant of whether centers granted industry intellectual property, whether they allowed disclosure restrictions, and whether they were large investors in basic research. **[Wes, as the model is currently constituted, quality does NOT have an effect on intellectual property in a regression framework, although Table 5-13 does show a strong effect.]** Simply put,

[3] There is no clear pattern in Table 5-12 for the effects of quality on intermediate outputs, and regression analyses also indicate no statistically significant effects one way or another.

academic quality appears to be the principal factor influencing the decision of a university-industry research center of whether to adopt an industrial or more traditionally academic orientation in their activity.

LUCIEN AND WES: I THINK WE WILL NEED TO REPORT THESE REGRESSION RESULTS SOMEWHERE -- PERHAPS IN AN APPENDIX WE CANNOT SIMPLY ASSERT THEM.

[Table 5-13 about here]

The last step in our analysis of the role of quality was to examine the ways through which academic quality affects funding by industrial sponsors. Does industrial funding flow to centers which do the most for industry or to centers which the top-ranked faculty? Does industrial funding go to centers with top-ranked faculty regardless of their disclosure or intellectual property policies?? Conversely, we wanted to know whether less highly ranked or lower quality centers were somehow more friendly to industry in terms of their intellectual property or disclosure policies, or as a result of their perceived lower quality more subject to industry influence and control.

The findings of these analyses lines were particularly interesting. First and foremost, it became abundantly clear that industry funding follows quality. In other words, industry funding flows to the top researchers at the top places. This findings is confirmed by our interviews with industrial R&D leader who said that their organizations tend to locate and support the top people. Furthermore, our findings indicate that despite what firms say in this regard, disclosure restrictions or intellectual property policies tend not to matter in industry funding decisions. The results of regression analysis further confirm that academic quality is the principal factor in attracting industrial support. Second, funding of centers by universities themselves tended to concentrate in second-tier units. This may make sense as universities focus investments on boosting second-tier units upward into the first tier. Third, state funding tended to decrease with quality. This may reflect a political process, whereby resources are allocated according to political criteria rather than more meritocratic criteria - a suggestion which is line with the notion of "pork-barrel" research funding advanced by Roger Noll and Linda Cohen: though their analysis focuses on the federal level, there are good reasons to expect such forces to operate with even greater force in the states and on state legislatures. Fourth, there was no relationship between quality and federal funding. This is not so, however, when we look at the NSF and NIH separately (see table 5-15). Funding from both the NSF and NIH was, not surprisingly, concentrated in high-quality organizations. The results of this analysis clearly indicate that industry concentrates its funding at highly ranked centers, even when they tend not to address industry's immediate needs or offer policies which industry leaders state are important to effective research relationships between the universities and industry.

[Tables 5-14 and 5-15 about here]

Summary

In this chapter, we have seen that university-industry research centers face a tradeoff between the university's longstanding commitment to the traditional academic norms of basic research and the free flow of ideas on the one hand, and the advance of commercial technology on the other. In simple terms, university-industry research centers that are more committed to industry tend to be more productive in generating outputs of relevance to industry such as new products and processes, but in doing so they tend to sacrifice academic output. These centers are more productive with respect to commercial outputs because they also tend to sacrifice the more traditional norms and tenets undergirding the pursuit of *academic* science. That is to say, they are more willing to provide intellectual property to participating firms, to allow them to impose restrictions on information disclosure and publication, and to conduct applied research and development, and it is these activities that are associated with greater commercial productivity at
.

Thus, there appears to be a social benefit associated with these departures from the academic norm. As centers embrace commercial goals, their tangible and intangible effects on technical advance increase, at least in the short run. Moreover, the social cost of these restrictions may not be so significant if the alternative to conducting this research within university-industry centers is conducting the same research within industry subject to even greater restrictions. The nature of this tradeoff is fundamental to understanding university-industry research centers and to informing the broader structure of relationships between university, industry and government.

The nature and terms of this tradeoff are clearly affected by academic quality. In simple terms, higher rated, higher quality organizations are able to offset perceived industry demands for greater access to intellectual property or greater restrictions on scientific disclosure. Basically, we find that academic quality is the principal factor conditioning the terms of this tradeoff. Centers affiliated with top-rated departments are much less likely to depart from traditional academic norms and are correspondingly more productive in academic terms, that is, in the generation of research papers.

This finding has potentially important implications for both the long-term pattern of industrial support of university-industry research centers and government policies to encourage university-industry interaction. One potentially very significant implication is that industry support for university-industry research centers may be to some degree unstable. As it stands now, companies appear to be funding those faculty and centers who are least likely and least willing to engage in applied, industrially-relevant R&D, grant intellectual property, or agree to significant restrictions on disclosure of their findings. In other words, industry is choosing to fund the least "industry-friendly" researchers and centers. On the one hand, this is easy to understand: industry picks the best people and allows them to accomplish their work in an a more or less unfettered, traditional academic setting. On the other hand, it contradicts industry's stated preference for research partners which share its values. This, as we believe, is the source of the emerging and potentially great instability in the relationship between universities and industry, particularly as that relationship involves joint research centers. We further sense that this situation may well persist and worsen, at least in the short-run, in part because companies have no direct measure of the commercial productivity of university-industry research centers and thus, as we know from our company interviews, continue to rely on academic reputation as the indicator of who to fund. In fact, this may also help to explain the complaints of industry leaders that academic researchers and centers are far too inflexible. To the extent that corporations begin to realize that academic quality is at best very poorly correlated with the production of outputs of the greatest interest to them, we may begin to see them pull out of these relationships. And, that is precisely what our interviews with industrial R&D leaders suggest. Another possibility is that companies may begin to fund centers at less prestigious schools and departments, which are more likely to be both industry friendly and interested in producing commercially relevant outputs. However, our interviews with industry representatives indicate that even companies that are interested in downstream commercial outputs tend to concentrate their funding at the most prestigious universities. These interviews also reveal that these same companies are dissatisfied with the activity and output of the centers they support. Still another possibility is that industry begins to more forcefully demand that universities implement more stringent disclosure and intellectual property policies in return for industrial support.

These findings have a host of implications for public policy. Paramount among them is realization of the off-setting role of publicly-supported research. At bottom, it is the ability to attract public research support which enables the highest quality researchers to effectively resist disclosure restrictions. The importance of this cannot be under-estimated especially since these researchers (by virtue of their quality rankings) are most likely to generate important scientific advances. Another possibility is for policy-makers to support centers composed of universities of different levels of academic quality. This would take advantage of the already evident division of labor in university research where the top quality organizations focus on basic research and cutting edge problems, while lesser quality institutions are able to work more flexibly with industry on applied problems with more direct and immediate commercial payoffs. Such a policy might have the joint advantage of allowing the highest quality researchers to continue to work in an open scientific environment with substantial support, while getting downstream outputs into the hands of industry more quickly than might happen otherwise. In saying this, we want to again emphasize that the success of such a policy change is likely to depend on continued strong support from government to advanced scientific research by the highest quality organizations. We will return to these issues following a brief recap of major findings in themes in the next and final chapter of this book.

Chapter 6

Continuity and Change:

University-Industry Research Relationships in the American System of Innovation

WILL ADD INMATERIAL FROM WES' DRAFT PAPER FOR NOLL

NEEDS LOTS OF WORK, IMPLICATIONS, BIG THEMES, SCENARIOS OF THE FUTURE

MAY WANT TO TRY TO INTEGRATE OR ADVANCE SOME MORE GENERAL CONCEPTUAL FRAMEWORK REGARDING THE ROLE OF THE UNIVERSITY IN THE INNOVATION PROCESS

In writing this book, we have sought to make two contributions. First, we have provided an empirical examination of the current status and effectiveness of university-industry research relationships as they are manifested in formal university-industry research centers. Second, we have sought to situate our understanding of these contemporaneous phenomena in the context of broader institutional trends in the evolution of the relationships among university, industry and government.

The main thrust of our work suggests that university-industry research relationships are rather extensive. Throughout this book, we have emphasized the fact that university-industry research relationships in general, and university-industry research centers in particular are not new, rather they are part of the very fabric of the evolution of the division of innovative labor in the twentieth century emerging alongside the rise of science-based industry. The formal university-industry research centers of the current day are thus the product of a century long process of organizational evolution, adaptation and experiment. Furthermore, our research has shown that the main impetus for these relationships has come from university actors manipulating the changing currents of industrial needs and shifting government priorities to obtain support required to advance their own scientific and technical agendas. We find little evidence to support the view that university-industry research relationships are the product of industrial interests attempting to manipulate the university for their own immediate ends. In fact, the university has considerably increased its role in the performance of research and development in the American economy over the course of the twentieth century and in particular over the past 25 years.

This book also suggests that the closer links between universities and industry manifested in university-industry research centers pose a considerable challenge to the traditional conception of free and open academic science. The ability of outside industrial actors to influence the research agenda of these centers, the imposition of restrictions on information disclosure and communication even within the same faculties and centers, the involvement of these centers in conferring intellectual property, all contradict the traditional tenets which have governed academic science. We no longer live and work in the kind of scientific world envisioned by Merton and others before him, where scientists openly and freely share the fruits of their labor in the quest for fundamental knowledge. Rather, in many fields of inquiry, more proprietary considerations help to shape and structure the agenda of science. This is the new reality of academic science. And, given the extent of university-industry research centers on university campuses across America, there is apparently no going back to what there was before.

That said, our work does not suggest that the closer integration of university and industrial science and even the imposition of more relevant and at times commercial considerations in the conduct and application of academic research will have negative implications for economy and society. In fact, this book suggests that university-industry research centers are rather productive, in fact more productive than most experts might have thought, both in terms of generating tangible and intangible outputs of applicability to industry and in producing traditional academic outputs whether those be contributions to the research literature or new generations of scientists and engineers. More to the point, a main message of this book suggests that the whole issue of whether universities and more specifically university-industry research centers, contribute to the advance or fundamental science or assist industry in developing more immediately relevant technology and products cannot be posed as an *either-or* proposition. Rather, our work suggests that the nature of this issue takes the form of a tradeoff--one that can and is affected by real decisions and social choices. We find that to the extent that universities want to contribute to more immediate technical advance and generate new products, product ideas and processes, they have found, and will continue to find, it necessary to grant firms greater control of their research agenda, to restrict the free flow of information, and confer intellectual property rights to industry. This is the price universities--and society more generally--will have to pay for closer university-industry ties and a more immediate university contribution to technical advance in industry. To the extent that universities see their main mission and objective as the pursuit of basic science and adding to the stock of fundamental knowledge, they will be best served by maintaining their long-held commitments to free, open, full and timely disclosure of research findings.

A major aspect of our work suggests that the division of innovative labor between the universities and industry is complex and distinguished by extraordinary variation across different fields of science, technology and industry. There is no single model for university-industry research relationships, nor is there any preordained optimal structure for such relationships. Rather, the ties between universities and industry vary greatly by field and are themselves informed by the historical evolution of institutional relationships between universities and industries and the role of government policies in shaping those relationships. In areas where there is closeness between science and industrial application, such as the new biotechnologies, the university is often the direct source of industrial and commercial applications; and scientists in universities and industry frequently work on essentially the same problems. In areas where there is considerable distance between science and industrial application, the institutional division of innovative labor is rather more complex. Some of these areas are characterized a more or less linear division of innovative activities, where university scientists devote their efforts to the pursuit of basic science and fundamental knowledge, while researchers in industry endeavor to apply elements of this basic knowledge and other sorts of know-how to develop new technologies and products. In other areas, such as computer-aided software engineering, university scientists work on more or less the same applied problems as industrial researchers, developing prototype systems which frequently spawn new business firms. And, in a few areas, industrial researchers actually work on problems of a more basic and fundamental nature than their colleagues in universities.

WES THIS WHOLE SECTION NEEDS TO BE REVISED, EXPANDED BOLSTERED IN LIGHT OF OUR DISCUSSION: WHY ISN'T THE UNIVERSITY MORE INVOLVED

At a somewhat deeper level, our work affords a number of conceptual insights of a more general theoretical nature on the role of the university in advanced industrial economies. This is an issue to which very little attention has been devoted, and while it is one which is beyond the scope of this book and which certainly deserves considerably more attention than we can devote here, we provide the following brief reflections in the hope they will help to stimulate a more general discussion of this important issue. In our view, both the increasing role of the university in performing research and development and the rise of closer and more formal ties between universities and industry can be seen as reflective of a more general economic trend toward the use and integration of science, technology and knowledge production as sources of wealth, productivity, and economic growth. There has been an attendant shift in the university's social and economic function--from a traditional emphasis on the transmission and reproduction of knowledge via its education and training functions (up until roughly the mid-nineteenth century) to its increased emphasis on direct knowledge production of both a fundamental and applied nature since that time. The more current rise and widespread diffusion of formal institutional ties between universities and industry prompted and supported by government can thus be seen as the product of a century-long process of organizational evolution, experimentation, and adaptation to an increasingly innovative, science-based, and knowledge-intensive economy. Given its historical evolution and organizational structures and incentives, the contemporary university provides a virtually unique organizational context for pursuing alternative pathways and ideas, generating new knowledge, and unleashing the creative potential in ways that other more focussed and directed economic institutions simply cannot.

The consequence is that the university has become to play an increasingly important and direct role in technological and economic life. It is this complex and multi-variegated process of increasing organizational integration of the university into the economy which is causing an attendant set of disruptions and transformations in the norms, tenets and incentives which have governed academic science. In an era of increasingly knowledge-based economic activity and science-based industry, it should come as little surprise that the university is more involved in research of greater relevance to and conducted with closer ties to economic actors. In fact, the question one might want to pose is: Given such a trajectory, why isn't the university more directly involved in innovative activities of a more direct economic sort. The answer here lies partly in the evolution of the historical relationships, or division of innovative labor between the universities, industry and government, and also in the powerful effect of established norms and incentive structures which inform scientific and technical activity in universities and industry. In effect, we would suggest that it is precisely the persistence of the norms of free and open scientific inquiry, curiosity-driven research, and the autonomy of the individual investigator that has made it difficult to connect the pursuit of university science to the more focussed and directed pursuit of more immediately relevant and applicable endeavors in industry. We qualify this statement simply by noting that this problem manifests itself less in fields of science and technology where there is a close relationship between basic scientific advance and the creation of commercial technologies and products, such as the new biotechnologies. The issue is thus not whether university-industry research centers have reached their peak, or whether they will expand or decline in the future. Rather, as part of a broader historical and institutional process of evolution and adaptation, we would expect the university to become more--not less--involved with directly applicable science, and hence industry, particularly in field where the two are already closely linked by the nature of science. The important question that remains is precisely what forms those evolving organizational relationships and mechanisms between university, industry and government will take.

. . . .

Appendix A:

Study Design and Methodology

The research presented in this book involved a combination of research methods and strategies, including historical research, field research, personal interviews, site visits, case studies and, most importantly, survey research. The research was designed to provide a comprehensive picture of the level and nature of the activities of university-industry research centers, and to examine the effects of university-industry research centers on technical advance in industry and the conduct of university research.

The first step was to identify the population of university-industry research centers nationwide. We used several techniques to do this. We began by examining existing lists and directors of university-industry research centers, for example, the *Gale Research Centers Directory*, the directory of *State Technology Programs in the United States* compiled by the Minnesota Department of Trade and Economic Development, National Science Foundation reports and other sources. We tested the accuracy and completeness of these lists by conducting short phone interviews with research administrators from 10 universities around the country. These interviews revealed that the existing lists were incomplete and contained out-of-date listings. Thus, we compiled our own list.

To develop this list, we conducted a national survey of research administrators at the 437 American universities and colleges which the National Science Foundation identified as having had industry-sponsored research and development during the 1981-88 period. We defined university-industry research centers as: (1) university-affiliated research centers, institutes, laboratories, facilities, stations or other organizations; that (2) conducted research and development in science and engineering fields; (3) had a total 1990 budget of at least $100,000; with (4) part of the budget consisting of industry-sponsored funds. We defined a center as *university-affiliated* if it received university budgetary contributions, employed university personnel and used university-owned facilities. We excluded academic colleges, departments and individual faculty investigators engaged in private consulting or industry-sponsored research outside the context of a formal center.

Research administrators for each of the universities which received industrial funding were contacted by telephone and asked to provide a list of university-industry research centers that met the operational criteria. As a result of this phone survey, 386 (88.3 percent) of the universities responded. Of the responding universities, 203 reported having affiliated university-industry research centers that met the operational criteria while 183 reported having none. During this phase of the research, a total of 1,074 university-industry research centers were identified. We then compared the results of the phone survey to the lists of university-industry research centers available from the various directories to verify the responses. This revealed a number of discrepancies. In these cases, university research administrators were sent both lists of centers and asked to correct any discrepancies. We also used this technique to obtain responses from universities that would not provide lists of their centers. We sent them the lists of university-industry research centers we obtained from the directories and asked them to verify whether or not this list was accurate. This procedure both improved the accuracy of the list of university-industry research centers and yielded responses from 18 additional universities that did not respond to the phone survey. This survey ultimately achieved a response rate of 92.4 percent and identified a total of 1,466 university-industry research centers affiliated with 213 American universities and colleges.

We then conducted a mail survey of this population of university-industry research centers to obtain more detailed information on their activities, expenditures, sources of funds, contributions to technical advance, and impacts on academic science and the university's research mission. To develop the survey questionnaire, we built upon the existing social science and historical literatures concerning innovation and university-industry research efforts and conducted field research consisting of site visits to a number of university-industry research centers. We also solicited comments from leading academics and experts in the field, directors of university-industry research centers, government officials, industrial R&D managers and industrial participants in university-industry research centers. (The survey questionnaire is included in Appendix B).

The survey was administered to the directors of all 1,466 university-industry research centers that we identified in earlier stages of the research. We took a number of steps to ensure the validity of the survey responses. In analyzing the responses, 184 of the research centers failed to meet our definition of a university-industry research center because they were no longer in operation or were too recently established. We removed these centers from the sample population, reducing the number of university-industry research centers to 1,282. In total, the survey yielded useable questionnaires from 511 university-industry research centers at 160 universities and colleges for a response rate of 39.9 percent (Appendix C provides a list of universities represented in the sample of university-industry research centers).

After the survey results were in, we conducted a survey of non-respondents to assess whether our survey respondents were representative of the overall population of university-industry research centers. We randomly selected a group of 140 university-industry research centers from the 771 university-industry research centers that did not respond to the original survey. These 140 non-respondents were asked to participate in a short telephone follow-up survey. Of these 140 non-respondents, 116 were successfully contacted and 73 agreed to participate. We learned that of the 43 centers that were contacted but did not participate in the follow-up telephone survey, 34 did not meet the definition of a center. This suggested that the actual number of university-industry research centers was less than initially thought. We estimated that 192 of the remaining 655 non-responding university-industry research centers were also ineligible by extrapolating from the 29.3 percent (34 of 116) of the non-responding university-industry research centers that did not meet the eligibility criteria. Thus, our final estimate of the number of university-industry research centers existing in 1990 is 1,056 for an adjusted survey response rate of 48.4 percent.

We compared differences in the nature and level of activities between respondents and non-respondents. Although there are differences between respondents and non-respondents, non of these differences are statistically significant. In other words, respondents and non-respondents are similar in terms of total annual budget, number of research and development projects, and number of companies providing funding support in 1990, as well as the share of effort allocated to R&D, technology transfer, technical assistance, education and training, and entrepreneurship. These results indicate that the university-industry research centers in the sample are representative in terms of the scale and composition of their activities of the national population as a whole.

We also used a variety of other sources of information and data to provide a broader and more complete understanding of the origins, evolution, role and implications of university-industry research relationships. We visited a sample of university-industry research centers and conducted interviews with center directors, participating faculty and university administrators to gain a deeper and more compete understanding of their organization and administration as well as their implications for academic science.

We also conducted interviews with industrial participants to obtain their views on the effectiveness of university-industry research centers (versus other forms of industrial R&D and industrial support for academic science), and to explore the relationship between the restructuring of industrial R&D and increasing industrial support for university research. These interviews were conducted with managers in industrial firms in five industrial sectors (computer hardware and software, biotechnology, chemicals, and advanced materials to gain their perspective on the effectiveness of university-industry research relationships in general and university-industry research centers in particular. Interviews were conducted with large and small firms in each sector, and with multiple contacts in each firm to limit bias by obtaining a variety of perspectives from executives, managers and technical staff engaged in various facets of university-industry relationships.

We conducted a review of the historical and institutional literatures on university research and industrial R&D, as well as major government, agency, industry and trade journal reports on relevant topics for the twentieth century. In doing so, we compiled and analyzed existing historical data on trends in the performance and funding of university research during the post-World War II era, and for as much of twentieth century as data was available.

FIRM INTERVIEW INSTRUMENT

I. Greeting and Introduction

Hello. We are currently conducting a project at Carnegie Mellon University on industry's relationships with universities, specifically with industry funded research centers at universities. This project is funded by the National Science Foundation and the Ford Foundation. We have already completed a major report on the topic of university-industry research centers, a copy of which we would be happy to send to you right away if you would like. We are also writing a book on this subject to be published by the Oxford University Press in 1996.

We would greatly appreciate about a half an hour to 45 minutes of your time to answer some questions and provide us some background on of your company's interaction with universities and university-industry research centers (UIRC). For your information, we define a UIRC as any university-affiliated research center, institute, laboratory, facility, station or other organization that conducts research and development in science and engineering fields and has an annual budget of at least $100 thousand dollars, at least some of which is provided by industry.

We have a great deal of experience using company confidential information in our research and all information you provide will be kept strictly confidential. We have also developed our questions so that they can be answered with a minimum amount of your time.

Before we begin, can you tell me:

1. What is your official title and main area of your responsibility?

2. What responsibilities do you have with regard to funding university research?

In addition to this phone interview we would like to obtain some background on the scientific and engineering activities of your company that relate to its involvement with university research. We have prepared a brief, two-page questionnaire that we would like to have completed by the individual most responsible for managing your companies~ university research relationships. If this person is someone other than yourself, can you tell us who that is and how to reach him or her so that we may fax them this survey? Thank you.

II. Interview Questions

A. Company Information

We would like to start by asking you for some general background information on your company and the scope and importance of your company's science activities:

1. How important is basic research, equivalent to the type done at universities, to your company's new product and process development?

2. What are your primary sources of science and technology? (e.g. internal R&D, interaction with other firms in the industry, customers, suppliers or universities).

3. How important are universities as one of these sources, relative to the others?

4. What fields of research are most important to technical advance within your company?

5. What fields of university research are most important to technical advance within your company?

6. To the extent that they may be different from the fields of science you identified in the previous question, what fields of university research are most important to technical advance within your company?

B. Description of the Firms Interaction with Universities.

I would now like to ask you some questions about the nature and style of your company's interaction with universities.

1. Can you tell me if your company is currently funding research at universities or if it has funded such research in the past?

2. [If yes] Has any of this funding been provided to formal university-industry research centers?

3. In the last five years, have their been any corporate-level decisions that have lead to an increase or decrease in the overall funding of university research.

4. [If not answered in the previous response] What were these decisions?

5. [If not answered in the previous response] Does your company plan to increase, decrease

or maintain its current level of funding of university research?

6. [If yes] What is the reason for this change?

7. Does your company see the universities it funds as direct contributors to your corporate research effort?

8. [If yes] What form does this expected contribution take?

______ to improve existing products

______ to improve existing processes

______ to introduce new products

______ to introduce new processes

______ to make existing corporate R&D projects more efficient

______ other:

9. Which of these are the most important?

10. Given these expectations, how satisfied has your company been with the contribution of universities in each of these categories [where identified above]?

______ to improve existing products

______ to improve existing processes

______ to introduce new products

______ to introduce new processes

______ to make existing corporate R&D projects more efficient

______ other:

11. Do you have an idea of what the approximate pay-off period associated with your company~s investment in university research is?

12. Aside from direct contributions to your company's research effort, in what other ways does your company expect to benefit from its interaction with universities?

_______ early or proprietary access to research findings prior to public disclosure

_______ proprietary control over patents or other intellectual property resulting from the university's research

_______ access to a network of scientists involved in research in areas important to your company

______ access to faculty as consultants

______ a window on new scientific and technological developments

______ opportunity for industry personnel to work within the center

______ participation in educational programs

______ access to a source of prospective R&D personnel employees

______ other:

13. Which of these are the most important?

14. Given these expectations, how satisfied has your company been with the contribution of universities in each of these categories [where identified above]?

______ early or proprietary access to research findings prior to public disclosure

_______ proprietary control over patents or other intellectual property resulting from the university's research

_______ access to a network of scientists involved in research in areas important to your company

_______ access to faculty as consultants

_______ a window on new scientific and technological developments

_______ opportunity for industry personnel to work within the center

_______ participation in educational programs

_______ access to a source of prospective R&D personnel employees

_______ other:

15. [If "access to a source of R&D personnel" is important] To what extent does your company's access to the university students as future R&D personnel depend on your company's actual funding of university research?

16. What benefits do you believe universities expect from their interaction with industry?

17. In your view, are these expectations of academia at odds with your company's goals in interacting with universities?

18. How do you decide whether or not to fund a university group?

19. Are any specific criteria employed?

20. If so, what are they?

21. Does it matter that a school is among the top-ranked research universities?

22. How important is philanthropy as a criteria for funding university research relative to the other benefits your company expects?

23. Roughly what fraction of your company's interaction with universities takes place with formal university research centers?

24. [If the company funds centers specifically] Is there anything specific about formal university-industry research centers that attracts funding from your company?

25. In what other ways, aside from formal centers, is your company involved with universities?

C. Firm's Specific Experiences with UIRCs.

[If the company has had no involvement with formal centers but has funded university research, ask this question regarding the company's university relationship with which it has been the most involved.]

Now I would like to ask you some questions about your experience with university-industry research centers. These questions are very important to us since our project and our book deal with UIRCs specifically.

Again, we define a UIRC as any university-affiliated research center, institute, laboratory, facility, station or other organization that conducts research and development in science and engineering fields and has an annual budget of at least $100 thousand dollars, at least some of which is provided by industry.

1. With respect to your company's relationship with the formal university research center with which it has the most interaction, can you tell me a little about the center, its areas of activities, its size, and other corporate participants?

2. Did the impetus behind the relationship's formation come from the center or from your company?

3. [If it came from the company] How did your company learn about the activities of the center?

4. Is the center part of any of the National Science Foundation's university research center programs?

5. [If yes] Did this have any influence on your company's decision to get involved with the center?

6. How does your company attempt to apply the research performed at the center to actual products or industrial processes?

7. What challenges does your company face with respect to applying the research performed at the center to actual products or industrial processes?

8. Does your company have any explicit expectations of the center regarding the dissemination and disclosure of research findings that your company at least partially funded? For example:

   ______ early or exclusive access to UIRC research results

   ______ limits on the extent to which center faculty or students can communicate these findings to others

   ______ the option of screening papers before publication, delaying publication or deleting specific information from publications

______ the nature of the research that is conducted

9. How does your company's relationship with formal university research centers differ from its relationship with universities generally, for example with respect to:

______ the nature of your interaction with the university researchers

______ how your company expects to benefit from these relationships

______ center affiliated students versus other students?

______ other differences

D. Appropriability Issues

Next I would like to ask you some questions regarding possible concerns that your company may have regarding its interaction with universities. Universities operate in a different and more open environment than companies do, as you know.

1. To what extent is your company concerned with the possibility that the results of the research they fund might be better exploited by other companies that participate in the center's research?

2. To what extent is your company concerned with the possibility that the results of the research they fund might be exploited by rivals which have not contributed to the funding of the UIRC research?

3. Overall, what are your company's biggest concerns with respect its involvement in university research? These concerns might include those we've just discussed concerning the use by other companies of university research or may be different concerns that we have not yet talked about?

4. Are there any other benefits to funding university research or university-industry research centers that we have not yet talked about that you would like to discuss?

III. Closing and Thank You

Thank you very much for your time and your interesting answers, they will prove very valuable to our research project. [If a fax-survey recipient has been identified or if the respondent has agreed to fill it out himself] We will fax to [you/the person you identified] today the brief survey we mentioned earlier regarding additional background information on your company's scientific and engineering activities. Thank you again for your help.

References

Apple, Rima, "Patenting University Research: Harry Steenbock and the Wisconsin Alumni Research Foundation," *ISIS*, 80, (1989), pp. 375-394.

Arthur, W. Brian, "Industry Location Patterns and the Importance of History," CEPR Working Paper No. 84, Stanford University, 1986.

Arthur, W. Brian, "Urban Systems and Historical Path-Dependence," Unpublished paper, Stanford University, June 1987.

Bacon, R.F., "The Object and Work of the Mellon Institute," *Journal of Industrial and Engineering Chemistry*, vol 7, no. 4 (1915), pp. 343-347.

Birr, Kendall, "Science in American Industry," in D.D. Van Tassel and M. G. Hall, eds., *Science and Society in the United States*, (Dorsey Press, 1966)

Birr, Kendall, *Pioneering Industrial Research: The Story of the General Electric Research Laboratory* (Public Affairs Press, 1957).

Blumenthal, David, Michael Gluck, Karen Seashore Louis and David Wise, "Industrial Support of University Research in Biotechnology," *Science*, Vol. 231, (1986), pp. 242-246.

Blumenthal, David, Michael Gluck, Karen Seashore Louis, Michael Stoto and David Wise, "University-Industry Research Relationships In Biotechnology: Implications For The University," *Science*, Vol. 232, (1986), pp. 1361-1366.

Bok, Derek, *Beyond the Ivory Tower* (Harvard University Press, 1982).

Boyd, T.A., *Professional Amateur: The Biography of Charles Kettering*, (Dutton Press, 1957).

Branscomb, Lewis (ed.),. *Empowering Technology: Implementing a U.S. Strategy*, (Cambridge, MA: MIT Press. 1993)

Brooks, Harvey, "Research Universities and the Social Contract for Science," in Lewis Branscomb (ed.), *Empowering Technology*, (Cambridge, MA: MIT Press, 1993), pp. 202-234.

Bright, A.A., *The Electric Lamp Industry: Technological Change and Economic Development* *from 1800-1947*, (New York: MacMillan, 1949).

Bush, Vannevar, *Science--The Endless Frontier: A Program for Postwar Scientific Research*, (Washington D.C.: U.S. Government Printing Offices, 1945)

Chandler, Alfred, "The Structure of American Industry in the Twentieth Century: A Historical Overview," *Business History Review* (Autumn 1969).

Cochrane, Rexmond, *Measures for Progress: A History of the National Bureau of Standards*, (Washington DC: Government Printing Office, 1966).

Cochrane, Rexmond, *The National Academy of Science: The First Hundred Years, 1863-1963* (Washington D.C.: Academy Press, 1977).

Cortada, James, *The Computer in the United States: From Laboratory to Market, 1930 to 1960* (Armonk, NY: M.E. Sharpe, 1993).

Cox, Donald W., *America's New Policy Makers: The Scientists' Rise to Power*, (Chilton Press, 1964).

Dasgupta, Partha, and Paul David, "Information Disclosure and the Economics of Science and Technology," in G. Feiwel ed. Arrow and the Ascent of Modern Economic Theory, (New York: New York University Press, 1987).

Dasgupta, Partha, and Paul David, "Toward a New Economics of Science," Center for Economic Policy Research, Stanford University, (October 1992).

Dasgupta, Partha and Paul David, "Toward a New Economics of Science," *Research Policy* 23, 3 (May 1994), pp. 487-521.

Davis, C. and D. Kevles "The National Research Fund: A Case Study in the Industrial Support of Academic Science," *Minerva* 12, (1974). pp. 207-220.

Danielian, N., *AT&T: The Story of Industrial Conquest,* (1939).

Dennis, Michael Aaron, "Accounting for Research: New Histories of Corporate Laboratories and the Social History of American Science," *Social Studies of Science* 17, (1987), pp. 479-518.

De Toqueville, Alex, *Democracy in America*, Volume 2, (Boston: John Allyn Publishers, 1876).

Dickson, D. *The New Politics of Science* (New York: Pantheon, 1984).

Dorfman, Nancy, "Route 128: The Development of a Regional High Technology Economy," *Research Policy*, 12, (1983), pp. 299-316.

Dupree, Alvin Hunter, "The Founding of the National Academy of Science," *American Philosophical Society, Proceedings*, 101 (1957).

Dupree, Alvin Hunter, "The History of American Science: A Field Finds Itself," *American Historical Review* 71, (April 1966), pp. 863-874.

England, Robert Merton, *A Patron for Pure Science: The National Science Foundation's Formative Years, 1945-1957*, (Washington D.C., National Science Foundation, 1982).

Etzkowitz, Henry, "Making of an Entrepreneurial University: The Traffic Among MIT, Industry and the Military, 1860-1960," in E. Mendelsohn, M.R. Smith and P. Weingart, (eds.), *Science, Technology and the Military*, Vol. 12, (Kluwer Academic Publishers, 1988).

Etzkowitz, Henry, "Entrepreneurial Science in the Academy: A Case for the Transformation of Norms," *Social Problems*, Vol. 36, (February 1989), pp. 14-29.

Etzkowitz, Henry, "MIT's Relations With Industry: Origins of the Venture Capital Firm," unpublished paper (1990).

Falk, Charles E., *Technology in Retrospect and Critical Events in Science* , IIT Research Institute, (December 15, 1968).

Feldman, Maryann, and Richard Florida, 1994. “The Geographic Sources of Innovation,” *Annals of the Association of American Geographers*.

Feller, Irwin, "Evaluating State Advanced Technology Programs," *Evaluation Review*, Vol. 12, (1988), pp. 232-252.

Feller, Irwin, "Universities as Engines of R&D-based Economic Growth: They Think They Can," *Research Policy,* Vol. 19, (1990), pp. 335-348.

Feller, Irwin, "American State Governments as Models for National Science Policy," *Journal of*

Public Policy Analysis and Management (1991)

Flamm, Kenneth, *Creating the Computer: Government, Industry and High Technology,* (Washington DC: Brookings Institution, 1988).

Fosler, R. Scott, *The New Economic Role of American States*, (Oxford: Oxford University Press, 1988).

Frieberger, Paul and Michael Swaine, *Fire in the Valley: The Making of the Personal Computer* (Berkeley, CA: Osboren-McGraw Hill, 1984).

Gale Research Company, *Research Centers Directory*, (Detroit: Gale Research Company, various years).

Geiger, Roger, *To Advance Knowledge: The Growth of American Research Universities, 1900-1940*, (New York: Oxford University Press, 1986).

Geiger, Roger, *Research and Relevant Knowledge*, (New York: Oxford University Press, 1993).

Gluck, Michael E., David Blumenthal and Michael Stoto, "University-Industry Relationships In The Life Sciences: Implications For Students And Post-Doctoral Fellows," *Research Policy*, Vol. 16 (1987), pp. 327-336.

Government-University-Industry Research Roundtable, *Industrial Perspectives on Innovation and Interaction with Universities*, (Washington, D.C.: National Academy Press, 1991).

Graham, Margaret B.W., "Corporate Research and Development: The Latest Transformation," in Mel Horovitz (ed.), *Technology in the Modern Corporation: A Strategic Perspective,* (New York: Pergamon Press, 1986).

Graham, Margaret, "Industrial Research in the Age of Big Science," *Research on Technological Innovation, Management and Policy*, Volume 2 (1985).

Graham, Margaret, *RCA and the VideoDisc: The Business of Research* (New York: Cambridge University Press, 1986).

Gray, Denis, William Hetzner, J.D. Eveland and Teresa Gidley, "NSF's Industry-University

Cooperative Research Centers Program and the Innovation Process: Evaluation-Based Lessons," in Denis Gray, Trudy Solomon and William Hetzner (eds.), *Technological Innovation: Strategies for a New Partnership*, (Amsterdam: North-Holland 1986), pp. 175-193.

Hall, Courtney R., *History of American Industrial Science,* (Library Publishers, 1954).

Hounshell, David, "Edison and the Pure Science Ideal in 19th Century America," *Science,* (February 8, 1988) Vol 207, no. 4431.

Hounshell, David, "Industrial R&D," *Encyclopedia of the U.S. in the Twentieth Century,* (1994).

Hounshell, David and ???? Smith, *Science and Corporate Strategy*

Hughes, Thomas P., "The Order of the Technological World," in Robert Hall and Norman Smith, Norman (eds.), *History of Technology Vol V,* (Mansell Publishers, 1988).

Hughes, Thomas P., *Changing Attitudes Towards American Technology,* (New York: Harper and Row, 1962).

Hughes, Thomas P., *American Genesis: A Century of Invention and Technological Enthusiasm* (Viking Press, 1989)

Jaffe, Adam, "Real Effects of Academic Research," *American Economic Review,* Volume 76, (December, 1989), pp. 984-1001.

Jenkins, Reese, *Images and Enterprise: Technology and the American Photographic Industry, 1839-1925*, (Baltimore Johns Hopkins University Press, 1975).

Kenney, Martin *Biotechnology: The University-Industry Complex,* (New Haven: Yale University Press, 1986).

Kerr, Clark, *The Uses of the University,* (University of California Press, 1963).

Kevles, David, *The Physicists: The History of Scientific Community in Modern America,* (New York: Alfred A. Knopf, 1978).

Kidd, Charles V., *American Universities and Federal Research,* (Cambridge: Harvard University, Belknap Press, 1959).

Klevorick, Alvin, Richard Levin, Richard Nelson and Sidney Winter, "On the Sources and Significance of Interindustry Differences in Technological Opportunities," (Unpublished paper, March 1993).

Koppes, Clayton, *JPL and the American Space Program*, (New Haven: Yale University Press, 1982).

Kornhauser, William, *Scientists in Industry: Conflict and Accommodation*, (Berkeley CA: University of California Press, 1962).

Krimsky, Sheldon, "The New Corporate Identity of the American University, *Alternatives* Vol. 14, (May-June 1987), pp. 20-29.

Krugman, Paul, *Geography and Trade*, (Cambridge, MA: MIT Press, 1991).

Lampe, David (ed.), *The Massachusetts Miracle*, (Cambridge MA: MIT Press, 1988).

Leslie, Stuart, "Playing the Education Game to Win: The Military and Interdisciplinary Research at Stanford," *Historical Studies in The Physical and Biological Sciences*, Vol. 18, (1987), pp. 55-88.

Leslie, Stuart, "Profit and Loss: The Military and MIT in the Postwar Era," *Historical Studies in The Physical and Biological Sciences*, Vol. 21, 1, (1990), pp. 59-86.

Leslie, Stuart, *Boss Kettering: Wizard of General Motors* (New York: Columbia University Press, 1983)

Leslie, Stuart, *The Cold War and American Science*, (New York: Columbia University Press, 1993).

Levin, Richard, Alvin Klevorick, Richard Nelson and Sidney Winter, "Appropriating the Returns From Industrial R&D," *Brooking Papers on Economic Activity*, (1987), pp. 783-820.

Liles, Patrick,

Mansfield, Edwin, "Links Between University Research and Industrial Innovation," paper presented at the CERP/AAAS Conference on University Goals, Institutional Mechanisms, and the "Industrial Transferability of Research," March 18-20, 1994.

Mansfield, Edwin, "Academic Research and Industrial Innovation," *Research Policy*, Vol. 20, (1991), pp. 1-12.

Lundstrom, David, *A Few Good Men at UNIVAC*, (Cambridge, MA: MIT Press, 1987).

Merton, Robert, *The Sociology of Science*, (Chicago: University of Chicago Press, 1973).

Minnesota Department of Trade and Economic Development, *State Technology Programs in the United States*, (State of Minnesota, Office of Science and Technology, 1988).

Mowery, David C., and Rosenberg, Nathan. *Technology and the Pursuit of Economic Growth*, (New York: Cambridge University Press, 1989).

National Resources Planning Board, *Research- A National Resource*, Volumes 1-3, (Washington DC: U.S. Government Printing Office, 1938).

National Governors' Association, *Technology and Growth: State Initiatives In Technological Innovation*, (Washington, D.C.: National Governors' Association, 1983).

National Resources Committee, *Research--A National Resource*, (Washington D.C.: U.S. Government Printing Office, 1938).

National Science Board, *Science and Engineering Indicators*, (Washington, D.C.: National Science Board, 1993).

National Science Foundation, *Academic Science-Engineering R&D Expenditures, Fiscal Year 1989*, (Washington, D.C.: National Science Foundation, Science Resources Studies Division, 1990).

National Science Foundation, *National Patterns of R&D Resources: 1992*, (Washington, D.C.: National Science Foundation, 1992).

Nelson, Richard, "Institutions Supporting Technical Advance In Industry," *AEA Papers and Proceedings*, Vol. 76, (1986), pp. 186-189.

Nelson, Richard, (ed.), *National Innovation Systems: A Comparative Analysis*, (New York: Oxford University Press, 1993).

Nelson, Richard, and Peck, M., eds., *Technology, Economic Growth, and Public Policy,* (Washington D.C.: Brookings Institution, 1966).

Noble, David, *America by Design: Science, Technology and the Rise of Corporate Capitalism,* (New York: Oxford University Press, 1977).

Norberg, Arthur, "The Origins of the Electronics Industry on the Pacific Coast," *Proceedings of the IEEE*, 64, 9, (September 1976), pp. 1314-1322.

Orlans, Harold, (ed.), *Science Policy and the University,* (Washington D.C.: Brookings Institution, 1968).

Osborne, David, *Laboratories of Democracy*, (Boston: Harvard Business School Press, 1988).

President's Council of Advisors on Science and Technology, *Renewing the Promise: Research-Intensive Universities and the Nation*, (Washington, D.C.: U.S. Government Printing Office, December 1992).

Price, Don, K. *Government and Science: Their Dynamic Relations in American Democracy,* (New York: New York University Press, 1954).

Price, Don K., *The Scientific Estate*, (Cambridge, MA: Harvard University Press, 1965).

Rees, John, *Industry Experience with Technology Research Centers*, (Washington, D.C.: U.S. Economic Development Administration, 1990).

Rees, John, "Universities and State Technology Centers," *Economic Development Commentary*, (Spring 1991), pp. 4-11.

Reich, Leonard, *The Making of Industrial Research: Science and Business at GE and Bell, 1876-1926*. (New York: Cambridge University Press, 1985)

Rifkin, Glenn and George Harrar, *The Ultimate Entrepreneur: The Story of Ken Olsen and Digital Equipment Corporation*, (Chicago: Contemporary Books, 1988).

Roberts, Edward, *Entrepreneurs in High Technology: Lessons from MIT and Beyond* (New York: Oxford University Press, 1991).

Rogers, Everrett and Judith Larsen, *Silicon Valley Fever: Growth of a High-Technology Culture*, (New York: Basic Books, 1984).

Rosegrant, Susan and David Lampe, *Route 128: Lesson's from Boston's High-tech Community* (New York: Basic Books, 1992).

Rosenberg, Nathan, *Technology and American Economic Growth,* (Sharpe Publishers, 1972).

Rosenberg, Nathan, *No Other Gods: On Science and American Social Thought* (Baltimore: Johns Hopkins University Press, 1976).

Rosenberg, Nathan, "How Exogenous is Science?" in Nathan Rosenberg, *Inside the Black Box*, (New York: Cambridge University Press, 1982), pp. 141-159.

Rosenberg, Nathan, and Richard Nelson, "American Universities and Technical Advance in Industry," *Research Policy,* Volume 23, (1994), pp. 323-348.

Samber, Mark, "University-Industry Cooperative Research in America, 1870-1954," (Carnegie Mellon University, Department of History, Paper prepared for the Carnegie Mellon University-Industry Project, 1990).

Saxenian, Annaelee, *Regional Advantage: Culture and Competition in Silicon Valley and Route 128*, (Cambridge MA: Harvard University Press, 1994).

Schumpeter, Joseph, *Capitalism, Socialism, and Democracy,* (Oxford University Press, 1950).

Servos, John, "The Industrial Relations of Science: Chemical Engineering at MIT," *ISIS*, (December 1980).

Servos, John, "Changing Partners: The Mellon Institute, Private Industry and the Federal Patron," *Technology and Culture*, Volume 35, Number 2 (April 1994), pp. 221-257.

Shapira, Philip, "The National Science Foundation's Engineering Research Centers: Changing the Culture of U.S. Engineering?" (West Virginia University, Regional Research Institute, 1989).

Sinclair, Bruce, *Philadelphia's Philosopher Mechanics: A History of the Franklin Institute* (Baltimore: Johns Hopkins University Press, 1974).

Smith, Bruce L., *The Rand Corporation: Case Study of a Non-profit Advisory Committee,* (Cambridge University: Harvard University Press, 1966).

Smith, Bruce L. *American Science Policy since World War II,* (Washington D.C.: Brookings Institution, 1990).

Smith, John K., "World War II and the Transformation of the American Chemical Industry," in E. Mendelsohn, M.R. Smith, and P. Weingart, P., (eds.), *Science, Technology, and the Military*, Volume 12, (Boston: Kluwer Academic Publishers, 1988).

Storr, Richard J., *The Beginnings of Graduate Education in America,* (Chicago: University of Chicago Press, 1953).

Strickland, Steven, ed., *Sponsored Research in American Universities and Colleges,* (American Council on Education Press, 1967).

Sturchio, Jeffrey L., "Experimenting With Research: Kenneth Mees, Eastman Kodak, and the Challenges of Diversification," unpublished paper.

Suits, C. Guy. Suits: *Speaking of Research*, (J. Wiley and Sons, 1965).

Tiffany, Paul A., "Corporate Culture and Corporate Change: The Origins of Industrial Research at the United States Steel Corporation, 1901-1929," (Paper presented at the Society of History of Technology, October 25, 1986).

Thackeray, Arnold, "University-Industry Connections and Chemical Research: An Historical Perspective," in National Science Board, *University-Industry Research Relationships: Selected Studies* (Washington D.C.: National Science Foundation, 1982), 193-233.

Thompson, Robert Luther, *Wiring a Continent: The History of the Telegraph Industry in the United States*, (Princeton: Princeton University Press, 1947).

U.S. General Accounting Office, *The Federal Role in Fostering University-Industry Cooperation*, (Washington, D.C., 1983)

U.S. General Accounting Office, *Engineering Research Centers: NSF Program Management and Industry Sponsorship*, (Washington D.C.: August 1988).

U.S. National Science Foundation, *University-Industry Research Relationships: Myths, Realities and Potentials*, (Washington, D.C.: National Science Board, 1982).

Veblen, Thorstein, *The Higher Learning in America: A Memorandum on the Conduct of Universities by Business Men* (Stanford, CA: Academic Reprints, 1954, orig. 1981).

Veysey, Laurence, *The Emergence of the American University*, (Chicago: University of Chicago Press, 1965).

Watkins, Charles, *State Programs To Encourage The Commercialization Of Innovative Technology*, (Washington, D.C.: National Governors' Association Center for Policy Research and Analysis, 1985)..

Watkins, Charles, *Programs For Innovative Technology Research In State Strategies For Economic Development*, (Washington, D.C.: National Governors' Association Center for Policy Research and Analysis, 1985).

Watkins, Charles, and Joan L. Wills, "State Initiatives To Encourage Economic Development Through Technological Innovation," in Denis Gray, Trudy Solomon and William Hetzer (eds.), *Technological Innovation: Strategies For a New Partnership*, (Amsterdam: North-Holland, 1986), pp. 69-87.

Weidlin, Edward and William Allen Hamor, *Glances at Industrial Research During Walks and Talks at Mellon Institute*, (New York, 1936)

Weidlin, Edward, "A Thumbnail History of Mellon Institute," in H. P. Klug, (ed.), *Science and Human Progress: Addresses at the Fiftieth Anniversary of Mellon Institute*, (Pittsburgh: PA: Mellon Institute, 1964),

Weiss, Paul "Science in the University," *Daedalus*, 93, (1964), p. 1184.

Weiner, Charles, "Universities, Professors and Patents: A Continuing Controversy," *Technology Review* (February-March 1986), pp. 33-43.

Whitney, Willis, "Research as a National Duty," *Science*, 43, (1916).

Wilgres, Daniel and S. Lingren, *A Century of Electrical Engineering and Computer Science at MIT, 1882-1982*, (Cambridge, MA: MIT Press, 1982).

Wise, George, *Willis Whitney: GE and the Origins of U.S. Industrial Research* (New York: Columbia University Press, 1985)

Worthy, James, *William C. Norris: Portrait of a Maverick*, (Cambridge MA: Ballinger Publishing Company, 1987).

Wyckoff, Andrew W., and Louis G. Tornatzky, "State-Level Efforts To Transfer Manufacturing Technology: A Survey Of Programs And Practices," *Management Science*, Volume 34 (1988), pp. 469-481.

1.. Robert Merton, "The Normative Structure of Science," orig., 1942, reprinted in Merton, *The Sociology of Science: Theoretical and Empirical Investigations* (Chicago: University of Chicago Press, 1973), pp. 274-275.

2.. President's Council of Advisors on Science and Technology, *Renewing the Promise: Research Intensive Universities and the Nation*, (Washington DC: U.S. Government Printing Office, December 1992), p. 17.

3.. Derek Bok, *Universities and the Future of America* (Durham: North Carolina, Duke University Press, 1990).

4.. "The Big Stars on Campus Are Now Research Labs," *New York Times*, Sunday, December 12, 1994, p. 1.

5.. See, Minnesota Department of Trade and Economic Development, *State Technology Programs in the United States*, State of Minnesota, Office of Science and Technology, (1988).

6.. Figures are reported in 1987 constant dollars from National Science Board, *Science and Engineering Indicators*, (Washington, D.C.: National Science Board, 1993).

7.. See, "Johns Hopkins Opens Equity Ownership to Faculty, University for the First Time," *Venture Capital Journal*, (February 1993), pp. 7, 15

8.. See, National Science Board, *Science and Engineering Indicators*, (Washington, D.C.: National Science Board, 1993).

9.. See, Paul David, David Mowery, and W. Edward Steinmueller, "University-Industry Research Collaborations: Managing Missions in Conflict," (Paper presented to the AAAS/ CEPR Conference on University Goals, Institutional Mechanisms and the Industrial Transferability of Research," Stanford University, March 18-20, 1994).

10.. Derek Bok, *Universities and the Future of America* (Durham: North Carolina, Duke University Press, 1990).

11.. John Armstrong, "Research and Competitiveness: Problems of a New Rationale," *The Bridge*, 23, 1 (Spring 1993), p. 6.

12.. See, "Turning off Spin-offs: Bucking a Trend University of Arizona Ends Direct Commercializing of Faculty Research," *Chronicle of Higher Education*, (July 21, 1995).

13.. See, Wesley Cohen, Richard Florida and W. Richard Goe, *University-Industry Research Centers in the United States* (Carnegie Mellon University, July 1994).

14.. Robert Merton, "The Normative Structure of Science," orig., 1942, reprinted in Merton, *The Sociology of Science: Theoretical and Empirical Investigations* (Chicago: University of Chicago Press, 1973), pp. 267-280.

15.. Arthur L. Stinchcombe, "University Administration of Research Space and Teaching Loads: Managers Who Do Not Know What Their Workers Are Doing," In Stinchcombe, *Information and Organizations* (Berekely, CA: University of California Press, 1990), pp. 312-337.

16.. Partha Dasgupta and Paul David, "Information Disclosure and the Economics of Science and Technology," in G. Feiwel (ed). *Arrow and the Ascent of Modern Economic Theory*, (New York: New York University Press, 1987); Dasgupta and David, "Toward a New Economics of Science," *Research Policy* 23, 3 (May 1994), pp. 487-521.

17.. See, Nathan Rosenberg, "How Exogenous is Science?" in Nathan Rosenberg, *Inside the Black Box*, (New York: Cambridge University Press, 1982), pp. 141-159; and, Nathan Rosenberg and Richard Nelson, "American Universities and Technical Advance in Industry," *Research Policy*, Vol. 23, 3 (1994), pp. 323-348.

18.. David Noble is the most ardent proponent of the industry-dominated university thesis. See, David Noble, *America by Design:*

Science, Technology and the Rise of Corporate Capitalism (New York: Oxford University Press, 1977).

19.. See, Henry Etzkowitz, "Entrepreneurial Scientists and Entrepreneurial Universities in American Science," *Minerva* 21 (1983), p. 232; Etzkowitz, "Making of an Entrepreneurial University: The Traffic Among MIT, Industry and the Military, 1860-1960," in E. Mendelsohn, M.R. Smith and P. Weingart, (eds.), *Science, Technology and the Military,* Vol. 12, (Kluwer Academic Publishers, 1988); Etzkowitz, "Entrepreneurial Science in the Academy: A Case for the Transformation of Norms," *Social Problems*, Vol. 36, (February 1989), pp. 14-29; Etzkowitz, "MIT's Relations With Industry: Origins of the Venture Capital Firms," (Unpublished paper, 1990); Roger Geiger, *To Advance Knowledge: The Growth of American Research Universities, 1900-1940*, (New York: Oxford University Press, 1990); Geiger, *Research and Relevant Knowledge* (New York: Oxford University Press, 1993); Stuart Leslie, *The Cold War and American Science* (New York: Columbia University Press, 1993).

20.. Edwin Mansfield, "Academic Research and Industrial Innovation," *Research Policy*, Vol. 20, (1991), pp. 1-12; and Mansfield, "Links between University Research and Industrial Innovation," Paper presented at the CEPR/AAAS Conference on University Goals, Institutional Mechanisms and the Industrial Transferability of Research," Stanford University, March 18-20, 1994.

21.. See, David Blumenthal, Michael Gluck, Karen Seashore Louis and David Wise, "Industrial Support of University Research in Biotechnology," *Science,* Vol. 231, (1986), pp. 242-246; and, David Blumenthal, Michael Gluck, Karen Seashore Louis, Michael Stoto and David Wise, "University-Industry Research Relationships In Biotechnology: Implications For The University," *Science*, Vol. 232, (1986), pp. 1361-1366; David Blumenthal, Nanyanne Causino, Eric Campbell, and Karen Seashore Louis, "Relationships between Academic Institutions and Industry in the Life Sciences: An Industry Survey," *New England Journal of Medicine* 334, 6 (February 8, 1996), pp. 368-73.

22.. See, David Blumenthal, "Academic Industry Relationships in the Life Sciences," Presentation to the MIT Industrial Performance Seminar, February 21, 1996.

23.. David Blumenthal, Nanyanne Causino, Eric Campbell, and Karen Seashore Louis, "Relationships between Academic Insitutions and Industry in the Life Sciences: An Industry Survey," *New England Journal of Medicine* 334, 6 (February 8, 1996), pp. 368-73.

24.. On the rise of science-based industry see, Chandler, Hounshell, Richard Nelson and Gavin Wright, ...

25.. See Rosenberg and Nelson, Geiger .....

26.. See, Robert Morgan et al [**LUCIEN PLEASE ADD THE CO-AUTHORS AS THE PUBLISHER WILL REQUIRE THEM]**, "Engineering Research in U.S. Universities: How University-Based Research Directors See It," Paper presented at the ASEE Annual Conference, June 28, 1994; Diane Rahm, "University-Firm Linkages for Industrial Innovation," Paper presented at the CERP/AAAS Conference on University Goals, Institutional Mechanisms, and the Industrial Transferability of Research," Stanford University, March 18-20, 1994.

27.. Figures for university-industry research centers are from Wesley Cohen, Richard Florida and W. Richard Goe, *University-Industry Research Centers in the United States* (Carnegie Mellon University, July 1994). The figure for NSF spending is from National Science Board, *Science and Engineering Indicators,* (Washington, D.C.: National Science Board, 1993).

28.. Cohen, Florida and Goe, *University-Industry Research Centers in the United States*

29.. See Lucien Randazzese, *Profit and the Academic Ethos: The Activity and Performance of University-Industry Research*

Centers in the United States (Pittsburgh, PA: Carnegie Mellon University, Department of Engineering and Public Policy, unpublished doctoral dissertation, January 1996).
30.. Thorstein Veblen, *The Higher Learning in America*, orig. 1918, (Stanford, CA: Academic Reprints, 1954), p. 48.
31.. See, Nathan Rosenberg and Richard Nelson, "American Universities and Technical Advance in Industry," *Research Policy*, Vol. 23, 3 (1994), pp. 323-348.
32.. Henry Etzkowitz, "Entrepreneurial Scientists and Entrepreneurial Universities in American Science," *Minerva* 21 (1983), p. 233.
33.. David Noble, *American by Design: Science, Technology and the Rise of Corporate Capitalism* (New York: Oxford university Press, 1977).
34.. See, Laurence Veysey, *The Emergence of the American University*, (Chicago: University of Chicago Press, 1965).
35.. We are indebted to David Hounshell for making these points.
36.. See, Veysey, *The Emergence of the American University*, (1965), p. 348.
37.. See, Richard Nelson and Gavin Wright, "The Rise and Fall and American Technological Leadership: The Postwar Era in Historical Perspective," *Journal of Economic Literature*, 30, (December 1992), pp. 1942-1943.
38.. See, Noble, *American by Design* (1977); and, Rosenberg and Nelson, "American Universities and Technical Advance in Industry," (1994), pp. 327-329.
39.. See, John Servos, "The Industrial Relations of Science: Chemical Engineering at MIT, 1990-1939," *ISIS*, (December 1980).
40.. See, Arnold Thackeray, "University-Industry Connections and Chemical Research: An Historical Perspective" in National Science Board, *University-Industry Research Relationships: Selected Studies* (Washington DC, National Science Foundation, 1982): 193-233. Se
41.. See, Noble, *America by Design*, (1977), p, 24; Nelson and Wright, "The Rise and Fall of American Technological Leadership," (1992), p. 1942.
42.. On the evolution of Edison's efforts from Menlo Park to General Electric, see, George Wise, "R&D at General Electric, 1878-1985," in David Hounshell (ed.) The R&D Pioneers (forthcoming).
43.. See, David Hounshell, "Industrial R&D," *Encyclopedia of the U.S. in the Twentieth Century*, (1994) for a comprehensive overview of the origins and evolution of industrial R&D in the United States. Also see, Leonard Reich, *The Making of Industrial Research: Science and Business at GE and Bell, 1876-1926*. (New York: Cambridge University Press, 1985); Stuart Leslie, *Boss Kettering: Wizard of General Motors* (New York: Columbia University Press, 1983); Margaret Graham, *RCA and the VideoDisc: The Business of Research* (New York: Cambridge University Press, 1986); George Wise, *Willis Whitney: GE and the Origins of U.S. Industrial Research* (New York: Columbia University Press, 1985): Thomas Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm* (Viking Press, 1989); Kendall Birr, "Science in American Industry," in D.D. Van Tassel and M. G. Hall, eds., *Science and Society in the United States*, (Dorsey Press, 1966); Kendall Birr, *Pioneering Industrial Research: The Story of the General Electric Research Laboratory* (Public Affairs Press, 1957); David Hounshell and Bruce Smith, *Science and Corporate Strategy....*
44.. See, David Hounshell, "Edison and the Pure Science Ideal in 19th Century America," *Science*, vol. 207, no. 4431 (February 8,

1988); Alvin Hunter Dupree, "The History of American Science--A Field Finds Itself," *American Historical Review*, 71 (April, 1966): 863-74.
45.. See, Servos, "The Industrial Relations of Science," (1980).
46.. See, David Hounshell and Smith, *Science and Corporate Strategy*
47.. Edward Gornowski, "The History of Chemical Engineering at Exxon" as cited in Thackeray, "University-Industry Connections in Chemical Research," (1982), p. 220.
48.. See, George Corner, *A History of the Rockefeller Institute, 1901-1953,* (Rockefeller Institute Press, 1965).
49.. See, Richard Nelson and Gavin Wright, "The Rise and Fall and American Technological Leadership: The Postwar Era in Historical Perspective," *Journal of Economic Literature*, 30, (December 1992), p. 1942.
50.. As David Hounshell has noted, the growth of the Mellon Institute was part of a broader civic project to revitalize the greater Pittsburgh region both by generating new businesses and just as importantly by conducting research in air pollution and new techniques for smoke abatement.
51.. See, John Servos, "Changing Partners: The Mellon Institute, Private Industry and the Federal Patron," Technology and Culture, Volume 35, Number 2 (April 1994), pp. 221-257; Edward Weidlin, "A Thumbnail History of Mellon Institute, in H. P. Klug (ed)., *Science and Human Progress: Addresses at the Fiftieth Anniversary of Mellon Institute* (Pittsburgh, PA: Mellon Institute: 1964); Edward Weidlin and William Allen Hamor, *Glances at Industrial Research, During Walks and Talks in Mellon Institute,* (New York, 1936). p. 29.
52.. David Hounshell has noted Mellon Institute was also involved in environmental research, playing a large role in the development of technology for the major smoke abatement initiatives developed by Pittsburgh business and political leaders.
53.. David Hounshell and John K. Smith, *Science and Corporate Strategy: DuPont R&D, 1902-1980*. (Cambridge: Cambridge University Press, 1988), pp. 290-293.
54.. See, Thackeray, "University-Industry Connections and Chemical Research," (1982): 219-220.
55.. Examples are from Thackeray, "University-Industry Connections and Chemical Research," (1982), pp. 215-217.
56.. See, Servos, "The Industrial Relations of Science: Chemical Engineering st MIT, 1900-1939," (1980), pp. 531-549.
57.. See, Servos, "The Industrial Relations of Science," (1980), pp. 538-540.
58.. See, Thackeray, "University-Industry Connections and Chemical Research," (1982), p. 213.
59.. See, James Cortada, *The Computer in the United States: From laboratory to Market, 1930 to 1960* (Armonk, NY: M.E. Sharpe, 1993), p. 32.
60.. See, Henry Etzkowtiz, "MIT's Relations with Industry: origins of the Venture Capital Firm," (1990), P. 12.
61.. Examples are David Mowery and Nathan Rosenberg, *Technology and the Pursuit of Economic Growth* (New York: Cambridge University Press, 1989); Rosenberg and Nelson (1994), Geiger (1986) and other sources.
62.. See, Rima D. Apple, "Patenting University Research: Harry Steenbock and the Wisconsin Alumni Research Foundation," *Isis* 80, (1989), pp. 375-394; Charles Weiner, "Universities, Professors, and Patents: A Continuing Controversy," *Technology Review*, (February-March 1986), pp. 33-43; Sheldon Krimsky, "The New Corporate Identity of the American University," *Alternatives* Vol. 14, (May-June 1987), pp. 20-29.

63.. In four cases of litigation WARF was able to require a license from each company--Eli Lilly, Parke Davis, Mead Johnson, and Abbot Labs. See, Apple, "patenting University Research," (1989).

. Thorstein Veblen, *The Higher Learning in America: A Memorandum on the Conduct of Universities by Business Men* (Stanford, CA: Academic Reprints, 1954). This book was written between 1900 and 1910 and published in 1918.

. On the Noyes-Walker affair, see, Servos, "The Industrial Relations of Science," (1980).

. Geiger, *To Advance Knowledge,* (1986), p. 179.

. Geiger, *To Advance Knowledge, (*1986), p. 180.

. See, Geiger (1986), pp. 186-190.

. See, Nathan Rosenberg, *No Other Gods: On Science and American Social Thought* (Johns Hopkins University Press, 1976): 179.

. See, Geiger, *To Advance Knowledge,* (1986), p. 97.

. See, Rexmond Cochrane, *The National Academy of Science: The First Hundred Years, 1863-1963,* (Academy Press, 1977), p. 364.

. See, National Resources Committee, *Research--A National Resource* (Washington DC: GPO, 1938), p. 169. This is also discussed in Geiger, *To Advance Knowledge,* (1986), pp. 260-264.

. See, Harvey Brooks, "Reflections on the Evolution of Science Policy in the United States: World War Ii and Beyond," (harvard University: unpublished paper, May 8, 1995

. Geiger, *To Advance Knowledge,* (1986), p. 254.

. See, Bruce Smith, *American Science Policy since World War II* (Washington DC: The Brookings Institution, 1990); J. Merton England, *A Patron for Pure Science: The National Science Foundation's Formative Years, 1945-1957* (Washington DC: National Science Foundation, 1982).

. Harvey Brooks, "Reflections on the Evolution of Science Policy in the United States: World War II and Beyond," (Harvard University, unpublished paper, May 8 1995), p. 3

. See, Mowery and Rosenberg, *Technology and the Pursuit of Economic Growth* (1989), p. 124.

. See, Leslie *The Cold War and American Science,* (1993), p. 6.

. Vannevar Bush, *Science--the Endless Frontier: A Program for Postwar Scientific Research*, (Government Printing Office, 1945). The report was just 34 pages long, with the remaining documentation released in four appendices.

. Vannevar Bush, *Science--The Endless Frontier* (Washington DC, 1945), pp. 12-13.

. See, England, *A Patron for Pure Science* (1982).

. Mowery and Rosenberg, *Technology and the Pursuit of Economic Growth* (1986), p. 125.

. On the early evolution of the computer industry see, Kenneth Flamm, *Creating the Computer: Government, Industry and High Technology* (Washington DC: The Brookings Institution, 1988); David Lundstrom, *A Few Good Men at UNIVAC* (Cambridge, MA: MIT Press, 1987); James Worthy, *William C. Norris: Portrait of a Maverick* (Cambridge, MA: Ballinger Publishing Company, 1987).

. Vannevar Bush, Hartley Rowe, Zay Zefferies, Arthur Raymond, and John von Neumann, *Report of the Panel on the McKay Bequest to the President and Fellows of Harvard College* (written 1949, published 1950).

. See, Harvey Brooks, "Some Reflections on the Past, Present and Future of U.S. Science and Technology Policy," (Paper prepared for the Merton C. Flemmings Lecture, MIT, March 23, 1995), p. 16.

. See, Paul Forman, "Behind Quantum Electronics: National Security as Basis for Physical Research in the United States, 1940-1960," *Historical Studies in the Physical and Biological Science* 18, 1 (1985), pp. 149-229; Stuart Leslie, *The Cold War and American Science*; David Noble, *Forces of Production*; Rebecca Sue Lowen, *Exploiting a Wonderful Opportunity: Stanford University, Industry and the Federal Government*, (Ph.d dissertation, Stanford University, 1990).

. The phrase distortionist debate was coined by Geiger in his review of Leslie's *The Cold War and American Science*. See, Roger Geiger, "Review of *The Cold War and American Science*," *Technology and Culture*, 35, 3 (1994), pp. 629-31. Additional works in this view include, Roger Geiger, *Research and Relevant Knowledge*; Geiger, "Science, Universities and National Defense, 1945-1970," *Orsis*, second series, 7 (1992), pp. 26-48; and Daniel Kevles, "Cold War and Hot Physics: Science, Security and the American State, 1945-1956," *Historical Studies in the Physical and Biological Sciences*, 20, 2 (1990), pp. 239-264.

. See, David Hounshell, *Science, Technology and Democracy in the Cold War and After: A Strategic Plan for Research in Science and Technology Studies*, (Report prepared for the National Science Foundation, 1995).

. We are indebted to Harvey Brooks for making this point.

. We thank Harvey Brooks for making these points in a comment on an earlier draft of this chapter. See, Harvey Brooks, "Impact of the Defense Establishment on Science and Education," Congressional Testimony, October 1970) ASK HARVEY FOR CITE OF THE TESTIMONY.

. See, Harvey Brooks, "Historical Perspectives on the Military Role in National R&D," (Harvard University, unpublished paper, May 30, 1986).

. We are indebted to Harvey Brooks for making these points,

. Data are from Roger Geiger, *Research and Relevant Knowledge: American Research Universities Since World War II* (New York: Oxford University Press, 1993), p. 298.

. See, Annalee Saxenian, *Regional Advantage: Culture and Competition in Silicon Valley and Route 128* (Cambridge: Harvard University Press, 1994); Susan Rosegrant and David Lampe, *Route 128: Lessons from Boston's High-Tech Community* (New York: Basic Books, 1992); David Lampe (ed). *The Massachusetts Miracle* (Cambridge: MIT Press, 1988); Edward Roberts, *Entrepreneurs in High Technology: Lessons from MIT and Beyond* (New York: Oxford University Press, 1991); Nancy Dorfman, "Route 128: The Development of a Regional High Technology Economy," *Research Policy* 12 (1983), pp. 299-316.

. See, Patrick Liles [appropriate cites are in vc chapter of Breakthrough Illusion]

. See, Etzkowitz, "MIT's Relations with Industry," (1990); A comprehensive, if somewhat journalistic, history of DEC is provided in Glenn Rifkin and George Harrar, *The Ultimate Entrepreneur: The Story of Ken Olsen and Digital Equipment Corporation* (Chicago: Contemporary Books, 1988).

. See, Roberts, *Entrepreneurs in High Technology* (1991).

. Bank of Boston, "MIT: Growing Businesses for the Future," (Economics Department, Bank of Boston, 1989.

. See, Richard Florida and David Talento, paper based upon interviews by Talento.

. As quoted in Saxenian, *Regional Advantage* (1994), p. 22.

. For a comprehensive account of these developments, see, Martin Kenney, *Biotechnology: The University-Industrial Complex* (New Haven: Yale University Press, 1984).
. See, Kenney, *Biotechnology* (1984).
. Data are from National Science Board, *Science and Engineering Indicators*, Washington, D.C.: National Science Board, 1993).
. See, Geiger, *Research and Relevant Knowledge* (1993), pp. 318-320,
. As cited in Geiger, *Research and Relevant Knowledge* (1993), p. 317. Also see, Luger and Goldstein....

Chapter 3: University-Industry Research Centers in the 1990s

. See Bruce Smith and Joseph Karlesky, *The State of Academic Science: The Universities in the Nation's Research Effort* (New Rochelle, NY: Change Magazine Press, 1977), pp. 65-78.
. James Botkin, Dan Dimancescu, and Ray Stata, *The Innovators: Rediscovering America's Creative Energy* (New York: Harper and Row, 1984), p. 284.
. Figures are from National Science Board, *Science and Engineering Indicators*, (Washington, D.C.: National Science Board, 1993), pp. 331, 342, 397.

. Non-responding centers devoted slightly less effort toward R&D than respondents and slightly more to education and technology transfer but these differences in proportion were not statistically significant (see the non-respondent survey results presented in Appendix B).
. Note, however, the sample of university-industry research centers is necessarily confined to centers in existence in 1990.
. Figures are from National Science Board, *Science and Engineering Indicators*, Washington, D.C.: National Science Board, 1993), pp. 406, 415. The National Science Foundation does not provide these data for 1990.
. While these estimates are supposed to reflect full-time staff only, several responses are extraordinarily high and the overall distribution of responses is extremely skewed (the skewness for total employment is 7.1). Thus, it may be that a small number of centers responded to this question incorrectly.
. See, U.S. General Accounting Office, Also see, National Academy of Engineering Report
. See, Irwin Feller and Roger Geiger, *The Dispersion of Academic Research During the 1980s: Report to the Andrew W. Mellon Foundation*, (Institute for Policy Research and Evaluation, Pennsylvania State University, May 1993).
. See, Linda Cohen and Roger Noll, *The Technology Pork Barrel*, (Washington DC: Brookings Institution, 1991); Cohen and Noll, "Privatizing Public Research," *Scientific American* (September 1994), pp. 72-77.
. John Armstrong, "Research and Competitiveness: Problems of a New Rationale," *The Bridge*, 23, 2 (Spring 1993), pp. 55-62.
.Figures are from National Science Board, *Science and Engineering Indicators*, Washington, D.C.: National Science Board, 1993), pp. 333-336.

. Here, it is important to note that the survey questionnaire asks each respondent to identify *all* the disciplines, industries and fields of technology to which their research is relevant.

. See, Dianne Rahm, "University-Firm Linkages for Industrial Innovation," Paper presented at the CEPR/ AAAS Conference on University Goals, Institutional Mechanisms and the Industrial Transferability of Research, (Stanford University, March 18-20, 1994).

. Henry Etzkowitz, "Entrepreneurial Scientists and Entrepreneurial Universities in American Science," *Minerva* 21 (1983), p. 233.

. Edwin Mansfield, "Links Between University Research and Industrial innovation," paper presented at the CERP/ AAAS Conference on University Goals, Institutional Mechanisms and Industrial Transferability of Research, (Stanford University, March 18-20, 1994).1994 CEPR paper

. Robert Morgan, Donald Strickland, Nimala Kannankutty and Joy Grillon, "Engineering Research in U.S. Universities: How University-Based Research Directors See It," Paper presented at the ASEE Annual Conference, (June 28, 1993).

. See, Henry Etzkowitz, Henry, "Entrepreneurial Science in the Academy: A Case for the Transformation of Norms," *Social Problems*, Vol. 36, (February 1989), pp. 14-29.

. Robert Morgan, Donald StricklanD, Nimala Kinnankutty and Carol Spellman, "Engineering Research in U.S. Universities; How Engineering Faculty View It," Paper presented at the IEEE-ASEE Frontiers in Education Conference, (November 7, 1994).

. Figures are from National Science Board, *Science and Engineering Indicators*, Washington, D.C.: National Science Board, 1993), p. 331

. Figures are from National Science Board, *Science and Engineering Indicators*, Washington, D.C.: National Science Board, 1993), p. 333.

. Figures are from National Science Board, *Science and Engineering Indicators*, Washington, D.C.: National Science Board, 1993), p. 331.

Chapter 4: University Research and Technological Change

. Government-University-Industry Research Roundtable and Industrial Research Institute, *Industrial Perspectives on Innovation and Interactions with Universities: Summary of Interview with Senior Industrial Officials*, Washington D.C., February 1991), p. 2-3.

. See, Nathan Rosenberg, "How Exogenous is Science?" in Nathan Rosenberg, *Inside the Black Box*, (New York: Cambridge University Press, 1982), pp. 141-159; and, Nathan Rosenberg and Richard Nelson, "American Universities and Technical Advance in Industry," *Research Policy,* Vol. 23, 3 (1994), pp. 323-348.

. Edwin Mansfield, "Academic Research and Industrial Innovation," *Research Policy*, Vol. 20, (1991), pp. 1-12.

. Edwin Mansfield, "Links Between University Research and Industrial innovation," paper presented at the CERP/ AAAS Conference on University Goals, Institutional Mechanisms and Industrial Transferability of Research, (Stanford University, March

18-20, 1994).

. See, Adam Jaffe, "The Real Effects of Academic Research," *American Economic Review*, (December 1989), Vol. 76, pp. 984-1001. Also see, Adam Jaffe, Manuel Trajtenberg, and Rebecca Henderson, "Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations," *Quarterly Journal of Economics*, 108 (1993): 576-598.

. See, Denis Gray, William Hetzner, J.D. Eveland and Teresa Gidley, "NSF's Industry-University Cooperative Research Centers Program and the Innovation Process: Evaluation-Based Lessons," in Denis Gray, Trudy Solomon and William Hetzner (eds.), *Technological Innovation: Strategies for a New Partnership*, (Amsterdam: North-Holland, 1986), pp. 175-193.

. See, David Blumenthal, Michael Gluck, Karen Seashore Louis and David Wise, "Industrial Support of University Research in Biotechnology," *Science*, Vol. 231, (1986), pp. 242-246; and, David Blumenthal, Michael Gluck, Karen Seashore Louis, Michael Stoto and David Wise, "University-Industry Research Relationships In Biotechnology: Implications For The University," *Science*, Vol. 232, (1986), pp. 1361-1366.

. Results from Blumenthal's 1984 survey suggested that academically funded biotechnology research was more productive that company research funded in-house. Blumenthal's latter 1994 results indicating no significant differences in this regard appear to be more reliable than the earlier results.

. See, David Blumenthal, Nancyanne Causino, Eric Campbell, and Karen Seashore Louis, "Relationships between Academic Institutions and Industry in the Life Sciences: An Industry Survey," *New England Journal of Medicine* 334, 6 (February 8, 1996), pp. 368-373.

. See, Richard Levin, Alvin Klevorick, Richard Nelson and Sidney Winter, " Appropriating the Returns from Industrial R&D," *Brookings Papers on Economic Activity* (1987), pp. 783-820; and, Alvin Klevorick, Richard Levin, Richard Nelson and Sidney Winter, "On the Sources and Significance of Interindustry Differences in Technological Opportunity," (Yale University, unpublished paper, 1993).

. The tangible and educational output and productivity statistics reported in this chapter were all computed after we trimmed the sample of what appear to be spurious outliers. We adopted the common standard for identifying possible outliers in a distribution, which identifies spurious outliers as those observations which lie outside the range of three inter-quartile ranges beyond the median observation. To be conservative, we computed the median only on the basis of positive valued observations for any given type of output. This practice typically led to dropping only a small number of observations, on the order of zero to three, for any given output.

. Figures are from National Science Board, *Science and Engineering Indicators*, Washington, D.C.: National Science Board, 1993), p. 286.

. See, for example, Irwin Feller, "Evaluating State Advanced Technology Programs," *Evaluation Review*, Vol. 12, (1988), pp. 232-252.

. The intermediate outcomes were elicited from survey respondents as categorical variables. For the purposes of summarizing the mean and mode values for these measures, we assigned the following values to them. For zero we simply sue zero. For the category "1 to 5 times," we use 3. For the category "6 to 10 times," we use 8. For "11 to 15 times" we use 13. And for the category "greater than 15 times," we use 15.

. To do so, again, we used the midpoints for all responses except the highest category (i.e. 15+ times), which was assumed to equal 15 (see summary scores for Table 4-4). Also, note that ranges (due to different treatment of blank responses) are not indicated for the intermediate outcomes results because these questions were closed-ended and clearly distinguished a "zero" response from a "don't know" response.

. In another question in our survey, UIRC directors were asked to indicate the number of center participating firms that had local R&D or manufacturing centers. Occasionally the response to this question was greater than the number indicated for the total number of participating firms, indicating some measurement error associated with this latter number. Accordingly, we tested the robustness of our findings to attempts to address this measurement error. When discrepancies between the reported number of local and reported number of total centers was small (i.e. less than 34 percent) we set the number of total firms to the number of reported local firms (firms with local R&D or with local manufacturing sites, whichever was higher). When the discrepancy between the local and total numbers was greater than 34 percent, the number of total firms was set to "missing." Intermediate outcome productivity numbers calculated based on these revised numbers for total participating firms were between 5 and fifteen percent lower than those reported in Table 4-5. No relationship was found, however, between this small discrepancy in new and original productivity numbers and other characteristics of the centers, such as size. Accordingly, we will report intermediate output productivity numbers in this and the following chapters using the uncorrected number of total participating companies.

. Cite Lucien thesis here.

. Lucien P. Randazzese, *Profit and the Academic Ethos: The Activity and Performance of University-Industry Research Centers in the United States*, Carnegie Mellon University. Ph.D. Thesis, 1995.

. Figures are from National Science Board, *Science and Engineering Indicators*, Washington, D.C.: National Science Board, 1993), p. 430.

. Since 26 percent of the centers grant patens to participating firms (see chapter 5), we do not know what fraction of the total 203 patents were assigned to the universities and thus cannot express the patent output of centers in our sample as a fraction of university output.

. This figure rises to 0.185 patents per million dollars of R&D when we include data from the outlier centers that have been dropped.

. Figures are from National Science Board, *Science and Engineering Indicators*, Washington, D.C.: National Science Board, 1993), pp. 333, 455.

. Figures are from National Science Board, *Science and Engineering Indicators*, Washington, D.C.: National Science Board, 1993), p. 428. These data are not available for 1990.

. This figure rises to 15.6 papers per million dollars of R&D when we include data from the outlier centers that have been dropped.

. See, Richard Levin, Alvin Klevorick, Richard Nelson and Sidney Winter, "“Appropriating the Returns From Industrial R&D," *Brooking Papers on Economic Activity*, (1987), pp. 783-820; Alvin Klevorick, Richard Levin, Richard Nelson and Sidney Winter, "On the Sources and Significance of Interindustry Differences in Technological Opportunities," (Unpublished paper, March 1993).

. In the future when we refer to regression analysis of factors affecting productivity we will be referring to the analysis of the factor in question alone on the right hand side of a regression specification.

. See, for example, W. Brian Arthur, "Industry Location Patterns and the Importance of History," (CEPR Working Paper No. 84, Stanford University, 1986); Arthur, "Urban Systems and Historical Path-Dependence," Unpublished paper, Stanford University, June 1987); Marayann Feldman and Richard Florida, "The Geographic Sources of Innovation," *Annals of the Association of American Geographers* (September 1994); Paul Krugman, *Geography and Trade*, (Cambridge, MA: MIT Press, 1991).

. Another 6.4 percent of total center effort is devoted to providing short-term assistance to industry in the solution of its technical problems, an activity that is related to technology transfer.

. Coopers & Lybrand, "Growth Companies With University Ties Have Productivity Rates Two-Thirds Higher Than Peers," *Trendsetter Barometer* (New York: Cooper & Lybrand, January 26, 1995).

. See, Government-University Industry Research Roundtable and the Industrial Research Institute, *Industrial Perspective on Innovation and Interactions with Universities: Summary of Interview with Senior Industrial Officials*, (Washington DC: National Academy Press, February 1991).

. Dianne Rahm, *University-Firm Linkages for Industrial Innovation: Final Report to the National Science Foundation* (University of South Florida, Department of Government and International Affairs, May 1995).

Chapter 5: Profit versus Priority

. Robert Merton, "The Normative Structure of Science," orig. 1942, reprinted in Robert Merton, *The Sociology of Science: Theoretical and Empirical Investigations* (Chicago: University of Chicago Press, 1973), p. 274.

. See, Robert Merton, "Science and the Social Order," 1938 [FIND COMPLETE CITE AND PAGE].

. Robert Merton, "The Normative Structure of Science," orig., 1942, reprinted in Merton, *The Sociology of Science: Theoretical and Empirical Investigations* (Chicago: University of Chicago Press, 1973), pp. 274-275.

. Partha Dasgupta and Paul David, "Information Disclosure and the Economics of Science and Technology," in G. Feiwel (ed). *Arrow and the Ascent of Modern Economic Theory*, (New York: New York University Press, 1987); Dasgupta and David, 1992. "Toward a New Economics of Science," *Research Policy* 23, 3 (May 1994): 487-521.

. Dasgupta and David, "Toward a New Economics of Science," *Research Policy* 23, 3 (May 1994), pp. 518.

. See, Nathan Rosenberg, "How Exogenous is Science?" in Nathan Rosenberg, *Inside the Black Box*, (New York: Cambridge University Press, 1982), pp. 141-159; and, Nathan Rosenberg and Richard Nelson, "American Universities and Technical Advance in Industry," *Research Policy*, Vol. 23, 3 (1994), pp. 323-348.

. David Blumenthal, Nancy Causino, Eric Campbell, and Karen Seashore Louis, "Relationships between Academic Institutions and Industry in the Life Sciences: An Industry Survey," *New England Journal of Medicine* 334, 6 (February 8, 1996), pp. 368-373.

. Note that in Tables 5-7, 5-8 and 5-10 "(per $10 million)" is calculated as outputs per dollar and averaged across centers while the "(per 100 researchers)" is calculated by examining the productivity of individual researchers within centers of a particular class, as described in Chapter 4.

. National Research Council. *Research Doctoral Programs in the United States: Continuity and Change*. Washington: National Academy Press, 1995.

. These summary data were used to derive measures of academic research quality for the centers in our data set. See Lucien R. Randazzese. *Profit and the Academic Ethos: The Activity and Performance of University-Industry Research Centers in the United States*. Ph.D. Dissertation, Carnegie Mellon University, December 1995.

. See, Gale Research Company, *Research Centers Directory*, (Detroit: Gale Research Company, various years); Minnesota Department of Trade and Economic Development, *State Technology Programs in the United States*, (State of Minnesota, Office of Science and Technology, 1988).

. National Science Foundation, *Academic Science-Engineering R&D Expenditures, Fiscal Year 1989*,(Washington, D.C.: National Science Foundation, Science Resources Studies Division, 1990).