CHAPTER ONE

Introduction

MARTIN KENNEY AND DAVID C. MOWERY

The twenty-first century is the century of knowledge-based economic growth. Recognizing this reality, national and regional governments in the industrial and industrializing economies have introduced policies and strengthened institutions to support innovation. One institution that has received significant attention in the course of these efforts is the research university. There are a number of reasons for the recent policy focus on research universities. Considerable evidence (Narin et al., 1997; Hicks et al., 2001) suggests that the dependence of technological innovation on advances in science and engineering research has increased in recent decades, a considerable change from the "trial-and-error" character of innovation in the late nineteenth and early twentieth centuries. Universities also play a unique role in both research and training, and their ability to expose graduates to the frontiers of scientific research provides a powerful mechanism for the transfer of knowledge and technology.

One of the most important recent U.S. initiatives in this area is the Bayh-Dole Act of 1980, which sought to promote the patenting and licensing by U.S. universities and federal laboratories of research advances based on federally funded research, based on the belief (which in turn had limited empirical support—see Eisenberg, 1996) that such policies would accelerate the commercialization of innovations based on publicly funded research (Berman, 2012). The post-1980 period has witnessed considerable growth in patenting by U.S. universities, and many of these patents have been licensed to private firms. Although it is far from clear that the Bayh-Dole Act in fact "caused" this growth in patenting and licensing, the Act is widely viewed as a success and has influenced the policies of other

Organisation for Economic Co-Operation and Development (OECD) and industrializing-economy governments seeking to encourage university–industry technology transfer (Mowery, 2009; Mowery et al., 2004). In addition, since 1980 state governments and universities in the United States have launched a dizzying array of initiatives for the support of new-firm formation and technology commercialization based on university research.

The intensive focus of many of these policies (including the Bayh-Dole Act) on patenting and licensing of university research advances overlooks the interactive nature of university–industry research relationships, which embody considerable feedback and iteration, rather than operating as a unidirectional flow of fundamental knowledge into industry application (Colyvas et al., 2002). In addition, these patent-focused reforms downplay the existence of multiple channels of interaction and knowledge flow between academia and industry. Our chapters indicate that a great deal of economically valuable technology transfer takes place outside the administrative channels created by most U.S. universities for technology licensing. Indeed, a number of important cases in this book highlight the movement of technology, people, resources, and knowledge from industry to university. The chapters demonstrate the importance of bidirectional and informal human and information flows, few if any of which are dependent on technology transfer offices. Technology licensing is only one of a multitude of channels through which technology and knowledge flow into and out of the university.

In spite of the endorsement by policy makers and university administrators throughout the United States of the value of "closer university–industry relationships," as well as the appearance of a large scholarly literature on this topic in the past two decades, we still know surprising little about the dynamics of these relationships, the effects of university research on regional economic development and the reverse, and the most appropriate approaches for assessing the benefits and costs of these relationships. The emphasis in recent U.S. policy on patent-based channels of interaction and knowledge transfer is reflected in the similarly "patent-centric" focus of much of the academic literature on university–industry research interactions, despite considerable evidence that patents and patent licensing play a modest role in many university–industry relationships.

The importance for industrial innovation of different channels of communication linking intrafirm R&D (research and development) to R&D in government or university laboratories was studied in a survey of R&D managers conducted by Cohen and colleagues (2002). They found that pharmaceutical executives assign greater importance to patents and license agreements involving universities and public laboratories than do other executives; even respondents from pharmaceuticals rated research publications and conferences as a more important source of information. In most other industries, patents and licenses of inventions from university or public laboratories were reported to be of little importance compared with publications, conferences, informal interaction with university researchers, and consulting (Agarwal and Henderson, 2002; Nelson 2012).

Another important feature of the relationship between academic and industrial researchers is its interactive character. Industrial research may in fact "lead" and influence the agenda of academic research in some fields, as was the case in the early stages of research on light-emitting diodes and semiconductors.[1] According to Lécuyer (2005a), Provost Frederick Terman of Stanford University encouraged William Shockley to locate his new firm near the university in 1955 to expose Stanford engineering faculty to new research in solid-state physics and electronics, and a future dean of Stanford's Engineering School served an "apprenticeship" of sorts at Shockley Semiconductor.[2] The movement of researchers between industry and academia facilitates this interactive relationship (for example, the move by Dr. Shuji Nakamura, a pioneering research in gallium-arsenide LEDs [light-emitting diodes], from Nichia Chemicals in Japan to the University of California, Santa Barbara, in 2000; see Chapter 7 in Mowery et al., 2004, for further discussion). Because many empirical studies of university–industry research linkages rely on cross-sectional analyses of patenting and licensing data, the evolution of industry- and campus-specific linkages over time often is overlooked, and these linkages inaccurately are characterized as unidirectional, with inventions and knowledge flowing exclusively from academia to industry, in another manifestation of the simplistic "linear model" of innovation.

This volume examines the evolution of university–industry relationships in research and innovation at six campuses of the University of California system, ranging from viticulture to computer science. This collection of studies enriches our understanding of the dynamics of university–industry relationships and regional economic development in several ways. First, the approach adopted in each of the chapters relies on historical analysis of the evolution of academic and industrial research, innovation, and regional development in a number of different specific fields of research. This approach enables a richer characterization of the interactive relationship between industrial and academic research and innovation than appears in many empirical analyses that focus mainly on patenting, article citations, and licensing. Second, our coverage of research fields is broader than recent historical studies, many of which have concentrated primarily on biotechnology or the life sciences generally. Although these fields have been and remain extremely important to the development of university–industry relationships in the United States during the past three decades, the unusual characteristics of research, innovation, and technology transfer in biomedical research and innovation means that the findings of these previous studies may not apply to other areas of academic research and university–industry relationships.

Our focus on a leading U.S. public research university, the University of California, also contrasts with that of previous historical studies of leading private U.S. universities such as the Massachusetts Institute of Technology (MIT) or Stanford. Inasmuch as public research universities in the United States in 2009 performed nearly 69 percent of all academic research and approximately 60 percent of federally funded R&D and accounted for 34 percent of bachelor's and more than 50 percent of doctoral degrees awarded in 2009 (National Science Board, 2012),[3] we believe that it is essential to examine their role in the evolving landscape of university–industry relationships.

It is also important to recognize some caveats associated with this volume's case studies. We cannot portray these cases as "representative" of the totality of university–industry research relationships in U.S. public universities or in the University of California (UC). Nor are the cases covered in this volume representative of the full diversity of regional economic impacts of research at leading public universities such as the UC and its various campuses. In addition, the historical approach adopted in these cases tends to highlight successes in research and innovation, rather than presenting a balanced account of successes and failures. Here, too, we cannot claim that our "sample" is in some sense representative. Moreover, the selection of case studies was influenced by author availability, meaning that equally interesting and important cases at other campuses were not chosen. Finally, as we note in the following pages, the University of California is an unusual institution, distinguished by its large size; by its network of campuses that are funded, managed, and evaluated as coequal research universities; and by the remarkable economic vitality of many regions of the enormous statewide economy. The chapters in this volume therefore are intended to present a rich portrait of the contrasting technological and economic dynamics of evolving university–industry relationships across a diverse set of research fields, regions, and university campuses, without making claims that the studies necessarily generalize to other regions or universities. We hope that these studies will stimulate similar research on other universities and research fields.

CALIFORNIA AND THE UNIVERSITY OF CALIFORNIA SYSTEM

California was admitted to the Union in 1849, and its economic growth through the remainder of the nineteenth century and much of the twentieth century was based on minerals extraction and agriculture. By 2012, it was the most populous state in the United States, and its economy (gross state product) ranks the state as one of the ten largest economies in the world. More significantly for this book, today the state has become a globally recognized center of innovation. One imperfect measure of the state's innovative performance is patenting. California's share of all U.S. utility patents granted (based on the reported residence of the first inventor on the patent) rose from 9.5 percent of the total utility patents granted in 1963 (the earliest date for which data are available) by the U.S. Patent and Trademark Office (2013) to 12.7 percent in 2012 (see Table 1.1). In 2012, California-based inventors accounted for the largest single share of U.S. utility patents among the fifty states, and the share of U.S. patents granted to California-based individuals trailed only those granted to Japanese inventors. During the 2000 to 2012 period, 45.6 percent of all U.S. venture capital invested went to California-based firms (calculated by authors from PricewaterhouseCoopers, 2013).

Coincidentally or otherwise, California also is home to ten of the world's top fifty universities (listed by their ranking in the 2012 rankings compiled by Shanghai Jiaotong University, 2012): Stanford, UC Berkeley, California Institute of Technology, UC Los Angeles, UC San Diego, UC San Francisco, UC Santa Barbara, UC Irvine, University of Southern California, and UC Davis. The geographic entity accounting for the second largest group of universities among the top fifty is a nation, the United Kingdom, with five research universities included in the ranking. The state of New York has four universities ranked among this elite group, none of which are public (Cornell is partially private and partially public). No

TABLE I.1. U.S. Patent Office utility patent grants by reported residence of primary inventor: Selected states and nations, various years.

Origin		*1963*	*1980*	*1990*	*2000*	*2010*	*2012*
Total	Number	45,679	61,819	90,365	157,494	219,614	253,155
U.S. total	Number	37,174	39,218	47,391	85,068	107,791	121,026
	Percentage of total	81.4	63.4	52.4	54	49.1	47.8
California	Number	4,357	5,053	6,946	17,491	27,337	32,107
	Percentage of total	9.5	8.2	10.7	11.1	12.4	12.7
Texas	Number	1,340	1,810	2,929	6,322	7,545	8,367
	Percentage of total	2.9	2.9	3.8	4	3.4	3.3
New York	Number	4,437	3,356	4,054	6,086	7,082	7,640
	Percentage of total	9.7	5.4	4.3	3.9	3.2	3
Massachusetts	Number	1,647	1,534	1,953	3,458	4,923	5,734
	Percentage of total	3.6	2.5	2.3	2.2	2.2	2.3
Japan	Number	407	7,124	19,525	31,295	44,813	50,677
	Percentage of total	0.9	11.5	20.9	19.9	20.4	20.0
Germany	Number	2,338	5,782	7,614	10,235	12,363	13,835
	Percentage of total	5.1	8.4	6.2	6.5	5.6	5.5

SOURCE: U.S. Patent and Trademark Office (USPTO), 2013.

other state in the United States has more than two public universities in the global top fifty.[4] Remarkably, seven of the ten leading California research universities are campuses of the University of California.

The University of California system was founded in 1869 with the establishment of the Berkeley campus, which focused on research and teaching in the humanities and natural sciences; in 1905 an agriculture-focused branch campus was founded in Davis, California (later UC Davis). A citrus experiment station established in Riverside in 1907 eventually became the nucleus of the UC campus in that city, founded in 1959. From its inception, the University of California also included a school of medicine, based in San Francisco, that became an independent UC campus in 1964. In 1919 a southern branch campus was established in Los Angeles; in 1928 this became the second University of California campus. From these beginnings, by 2012 the system had grown to include ten campuses that enrolled over 230,000 students, employed more than 13,000 academic faculty members, and spent $22 billion on operations.

Within this large university system that includes campuses distributed among diverse regional economies, the management of university–industry relationships and technology transfer within the UC system has long been a source of debate and conflict. One of the most complex and contested topics has been the relationship between systemwide and campus policies toward industry and faculty-generated intellectual property. Having been managed in a centralized fashion for much of the 1945–1980 period, a complex and incomplete process of decentralization in the formal structure of these policies and managerial responsibilities has characterized most of the decades since. But throughout the post-1945 period that witnessed the emergence of the University of California as a multicampus system of distinguished research universities, campus-level departments and faculty members have developed diverse "local" solutions to challenges of industry–university relationships in research and innovation. This diversity is hardly surprising, in view of the very different regional economic environments within which these campuses are situated and, importantly, the diversity among each campus's strengths in academic research and industrial innovation.

In the section immediately following, we summarize the case studies in the volume, by way of providing support for the discussion of overarching themes in the concluding section of this Introduction. Our conclusions also consider the implications of these studies for policy makers and university administrators.

CHAPTER SUMMARIES

Chapters Two and Three in this volume, respectively written by Christophe Lécuyer and Steven Casper, compare different UC campuses in an examination of the ways in which campus strategy and contrasting regional industrial landscapes produced different modes of university–industry interaction in the regional microelectronics and biotechnology industries in different parts of the state. The chapter by Christophe Lécuyer examines the development of the microelectronics industries of the San

Francisco, Los Angeles, and Santa Barbara regions, focusing on the interaction between industrial innovation and semiconductor-related research at UC Berkeley (UCB), UC Los Angeles (UCLA), and UC Santa Barbara (UCSB). UCB research in this area focused on silicon semiconductors for computers, benefiting from and in turn advancing the development of Silicon Valley. As Lécuyer shows, semiconductor research at UCLA pursued a different path as a result of the influence of the Los Angeles area defense industry, which had long-standing interests in communications. Microelectronics research at UC Santa Barbara focused on the exotic semiconductor materials that were of great interest to the Department of Defense and the Santa Barbara R&D laboratory operated by Hughes Electronics.

As Lécuyer points out, their contrasting paths of research reflected in part the fact that all three campuses hired faculty members with industry experience and frequently hosted visiting researchers from leading firms in their regional industries. Researchers from industry contributed technical insights to academic researchers, as well as communicating the research priorities and challenges of industry to academia. In addition, of course, the interaction between industry and academia at all three campuses aided in the placement of graduates seeking employment and was associated with growth in research support from industry. Faculty members from all three campuses also spent sabbaticals in firms that contributed to the transfer of technology to firms and (as in the case of UCB Professor Ron Rohrer's sabbatical at Fairchild), transferred semiconductor design software knowledge from regional industry to the university.

Chapter Three, by Steven Casper, on university–industry relationships in the California biotechnology industry discusses the role of UC San Francisco and UC San Diego as sources of licensed technology and start-ups. Casper shows that the San Francisco and San Diego regions developed different patterns of university-based innovation and commercialization. These contrasting patterns of regional development were based on the formation of local UC faculty spinoffs, Genentech in the San Francisco Bay area and Hybritech in San Diego, that pursued different business models. Both "anchor firms" enjoyed rapid growth and spawned other firms. In the case of Hybritech, the spawning of new firms was associated with the acquisition of the firm by the established pharmaceutical firm Eli Lilly. Lilly's acquisition of Hybritech led to the departure of many of the firm's managers (aided, in many cases, by their sale of equity stakes in Hybritech to Lilly as part of the acquisition), and these experienced executives sought other biotechnological inventions to commercialize. Genentech was an independent firm for far longer and also was the source of a number of spin-offs, although it too was eventually acquired by Roche, which purchased a 20 percent stake in the firm in 1990 and acquired the remainder of Genentech in 2012. Genentech managed corporate R&D as an "open science" model of intensive collaboration and publishing with academic scientists, while Hybritech was more commercially oriented and published comparatively little.

This chapter illustrates the complex dynamics at work between universities and regional firms and highlights the influence on these dynamics of the industrial firms (in this case new firms based on university research; in other cases described in this volume, established firms) that pursue links with university researchers. Surprisingly, the influence of these firms on the evolution of regionally contrasting patterns of university–industry relationships has received little attention in the large literature on this topic.[5]

Chapter Four by Martin Kenney and his coauthors examines the post-war history of electrical engineering at UC Berkeley by studying a number of projects that were associated with the transformation of electrical engineering at UCB from a practice-oriented "craft" into engineering science during the post-1945 period. The chapter highlights the complex and varied channels of interaction between UCB and the new and established firms that propelled the Bay Area's economic growth after 1960. Among the most important technological innovations from the UCB researchers are software-based advances, such as BSD UNIX, GENIE, and INGRES, none of which was the focus of patenting and licensing by the university. Data on patenting, licensing revenues, and even new-firm foundations fail to capture these contributions and overlook the bidirectional nature of the intellectual and personal interactions between UCB's EECS (Electrical Engineering and Computer Science) Department and local industry.

Chapter Five, by Walshok and West, examines the symbiotic relationship between UCSD and the wireless industry in San Diego, an especially interesting case of the coevolution of university and industrial research and innovation. Although his enterprise was not founded on UCSD-developed technology, the serendipitous decision of UCSD faculty member Irwin Jacobs to relocate his small start-up from Los Angeles to San Diego in 1971 initiated a powerful entrepreneurial dynamic that proved beneficial to the industry and the university. Walshok and West argue that this university–industry interaction benefited from an established cluster of government research facilities and technology-intensive aerospace firms in the San Diego region. During most of the period following the establishment of the UC campus in this region and the founding of Qualcomm, UCSD's most important role was providing trained personnel to the burgeoning regional wireless telecommunications industry. In addition to training undergraduate and graduate technical personnel, UCSD's extension programs provided advanced engineering courses, often taught by industry professionals, in wireless technology for engineers employed in local firms. The growth of the regional wireless industry initially depended less on UCSD research advances than on students trained in advanced research techniques.

Over time, UCSD became an important source of innovations, entrepreneurs, and new firms in wireless and related technologies that further accelerated the region's growth. The successful local telecommunications firms and the entrepreneurs who formed them became a source of significant gifts to the university that further strengthened the university's research strengths and stature in the rapidly advancing technologies of wireless telecommunications. As with other chapters in this collection, the UCSD narrative highlights the importance of distinguishing between the factors that may catalyze the initiation of a regional high-technology cluster's growth and the factors that sustain such growth over ensuing years.

Cyrus Mody's Chapter Six on UC Santa Barbara and the development of a regional scientific instruments "cluster" specializing in advanced electron microscopes describes a complicated interaction between university research and a start-up firm, Digital Instruments (DI), that was rooted in a unique UCSB master's degree program in scientific instrumentation. The chapter is one of very few studies of innovation in scientific instruments, a field of commercially significant innovation singled out by Nathan Rosenberg (1992) for its long-standing reliance on academic research (in many cases, based on the tinkering by academic users of instruments).[6] Digital Instruments was founded to commercialize a scanning tunneling electronic microscope (STM) that relied in part on the contributions of a visiting UCSB researcher based at IBM's Zurich R&D complex, the site of the work on STMs that led to a Nobel Prize—in this case, the movement of knowledge from industry to academia catalyzed academic innovation. Once established, Digital Instruments expanded its employment of UCSB graduate students from the instrumentation program and developed a series of important follow-on products, most of which initially relied on unpatented research advances from UCSB.

Mody's discussion of the development of probe microscopy emphasizes the informal, interactive character of the collaborations between university and industry researchers that spawned the development of advanced microscopes for applications in university and industrial research. Much of the research within UCSB that supported these innovations in industry was itself relatively applied, in contrast to the fundamental science that contributed to the founding of Genentech and other Bay Area biotechnology firms. Patent licensing was of secondary importance in facilitating these interactions at the inception of DI's development. As the links between Digital Instruments matured (and as new firms were spawned by Digital Instruments), the UCSB research advances increasingly were patented and licensed to DI and other regional firms, while DI expanded its financial and in-kind (for example, advanced instruments) contributions to research at UCSB.

The emergence of a scientific instrument industrial cluster in Santa Barbara thus did not initially depend on the licensing of UCSB technology or on sophisticated UCSB-based technology transfer activities. Instead, the cluster's growth was catalyzed by the entrepreneurial proclivities of key academic researchers at UCSB and a mutually beneficial flow of information and personnel between UCSB and DI. Moreover, as was the case with Hybritech, the acquisition of DI by another firm produced a wave of new firms founded by former DI employees in the region. The resulting scientific instruments cluster had significant economic benefits for the Santa Barbara region and enabled UCSB to become a center for nanotechnology research.

The relationship between U.S. agricultural innovation and public research universities has a long history (Ruttan, 1982; Kloppenburg, 1988; Wright, 2012), but studies of this relationship have had little influence on contemporary discussions of university technology transfer. Chapter Seven, by James Lapsley and Daniel Sumner, on the relationship between the Napa Valley wine industry and the Department of Viticulture and Enology at UC Davis highlights the ways in which university–industry relationships change over time as a result of the maturation and increasing innovative capacity of regional firms. The relationship between UC Davis research and the regional wine industry, however, also was affected by the increasing consumer demand for higher-quality wines that emerged in the 1960s.

The transformation in the technical capabilities of the Napa wine industry and the growth of the region's reputation for high-quality wine production benefited in the 1950s and 1960s from the flow of personnel, technology, and knowledge from the UC Davis viticulture program. Even in the early years of this transformation, UC Davis research publications played an important role. For example, the pioneering postwar Napa Valley vintner Robert Mondavi referred to *The Technology of Winemaking*, a book published by UC Davis professors, as his "bible." But much of the knowledge flowing from academia to the industry during this early period was "tacit" in nature, and Napa winemakers benefited from their proximity to UC Davis, as well as the UC vineyard in Oakville, the heart of the Napa Valley. Once again, much of the academic research that supported these improvements in methods and techniques in the region's wine industry was highly applied in nature and relied to a significant extent on the availability of a "test bed" in the unique climatic and growing conditions associated with the Napa wine industry. The UC Napa vineyard provided an important site for university experts and local vineyard owners to cooperate and learn from one another. The Oakville research station also was involved in extension services through its dissemination of improved rootstock to local growers.

In the 1950s, UC Davis was central to the formation of the American Society of Enologists, which linked university scientists to industry practitioners and contributed to the transformation of wine making into a science-based profession. As the Napa industry expanded and became more science based, by the late 1970s UC Davis enology and viticulture graduates were in great demand within the U.S. wine industry, leading to expanded enrollments in these academic programs. UC Davis University Extension, the self-supporting continuing education arm of the Davis campus, also began to offer short courses in wine and grape production. Finally, UC Davis researchers developed a number of research tools that were widely used in the global wine industry. None of these research tools was patented and licensed, instead being freely supplied to industry.

Since the 1980s, the Napa and other regional wine firms have expanded their support of UC Davis research and have made significant philanthropic contributions to the Davis program and campus. The long history of mutually beneficial interactions between the UC Davis campus and the regional (and increasingly, global) wine industry has operated largely through the long-established "agricultural research and extension" model that dates back to the late nineteenth century in the United States, rather than relying on the "Bayh-Dole" model of interaction that emphasizes patenting and licensing.

SUMMARY OBSERVATIONS

The diversity of knowledge-based interactions between university and "industrial" (including agricultural) innovation summarized in these chapters is remarkable, but some themes that are common to all of the studies provide useful perspectives for policy makers and university administrators who seek to encourage innovation and regional growth. These chapters also suggest some need for caution and innovation in the approaches adopted by university administrators and public officials to the evaluation of the contributions of research universities to national, state-level, or local economic development.

Even the studies examining the development of university–industry research relationships in specific technologies at different UC campuses, such as Casper's chapter on biotechnology and Lécuyer's chapter on semiconductors, highlight important contrasts in regional industrial and technological specialization that both influenced and were influenced by these relationships, reflecting different campus-level research specializations and the idiosyncratic character of regional economic development. Indeed, as in the contrast between Los Angeles or San Diego and the Bay Area, the regional industrial structure that predated the academic research discussed in these chapters influenced the direction of both academic and industrial innovation and development. There are also important contrasts among UC campuses and technology fields in policies toward intellectual property protection for academic inventions. For example, semiconductor research at UCSB was patented, but the early research on this campus dealing with scanning electron microscopes largely was not. Faculty resistance to patenting at UCB meant that a substantial portion of the research at UCB on semiconductor design software was not patented. The absence of patents on design software certainly did not discourage an intense interaction between UCB and industry researchers and arguably contributed to the broad adoption of this innovation within industry.

The portrait of university–industry interactions that emerges from these chapters thus is a complex and heterogeneous one, highlighting the diverse channels through which interactions occur, as well as the fact that interactions often flow in both directions between academia and industry. Moreover, it is inaccurate to characterize all of the research in the academic "ivory tower" that supports these interactions as basic research. The content of the academic research that has contributed to industrial innovation ranges from fundamental science to applied testing and other activities, depending on the field of research and the characteristics of the industry. The varied nature of this academic research further questions the validity of a "linear model" of innovation based on university–industry interaction.[7]

These characteristics of the interactions have several important implications. First, simple counts of academic patents or licensing revenues are poor measures of the "performance" of universities in developing or transferring technologies and knowledge to industry. Such data overlook the enormous variation among patents in their technological and economic significance or value, and patent counts alone also cannot account for the sharp contrasts in the economic value of patents among different fields of industrial innovation. Data on patenting or licensing revenues also overlook the existence of other forms and channels of transfer and interaction. The chapters by Kenney and his coauthors and by Lécuyer focus on numerous technologies (for example, INGRES, Project GENIE, BSD Unix, and semiconductor design software) that were not patented by UCB faculty, instead being provided to all interested parties in industry and academia. Lapsley's study of UC Davis and the Napa Valley wine industry similarly argues that the liberal dissemination of university research through a variety of formal and informal interactions, rather than patenting of inventions, was of great value to industry. Indeed, in several cases at UCB and UC Davis, the absence of patents on important advances contributed to an environment where industry researchers could share their expertise with university scientists, accelerating technical progress and adoption of key technological innovations. Moreover, the absence of patents did not preclude the establishment of new firms on the basis of these technological developments that enjoyed commercial success.

Patents and patent-based technology transfer are generally acknowledged to be more economically significant in biomedical technologies, as the chapter by Casper points out. Yet even in this sector, the characteristics of university–industry interactions at different UC campuses differed considerably. These contrasts suggest that no single template for designing and managing university–industry relationships is likely to be effective without flexibility to accommodate differences among industries, research fields, regional economies, and university campuses. Such flexibility should also accommodate contrasting approaches to the management of intellectual property and its licensing. Yet these contrasts and the associated importance of flexibility in strategy and policy remain insufficiently recognized in many U.S. universities' policies toward the management of university–industry relationships and patenting.

Another important theme that spans virtually all of these case studies, noted earlier, is the bidirectional nature of industry–university interactions and knowledge flows. Indeed, this characterization of these interactions applies equally to the flow of personnel, which is not uniformly a one-way flow based on the graduation of students or the departure of faculty to join firms. The academic research agendas in semiconductors and software at both UCB and UCSB, for example, benefited from the recruitment by academic departments of faculty from industry in both the United States and Japan. Equally important contributions to academic research flowed from faculty sabbaticals in industry and industry researchers' sabbaticals at universities. And in at least some of these instances, particularly in software, the two-way flow of personnel and ideas between industry and academic research benefited from the absence of patents covering key technological advances.

This bidirectional interaction between university and industry research and innovation also underscores the broader ways in which regional industry influences the evolution of university–industry relationships. The discussion in the chapters by Lécuyer and Kenney and his coauthors of the ways in which established firms in the San Francisco and Los Angeles areas influenced the research agenda and approach to commercializing their advances by UCLA and UCB researchers suggests that the influence of established firms on regional industrial and technological development may be as important as that of university "spin-offs" founded on the basis of academic research advances. Of course, in some cases, these spin-offs (for example, Cadence, Digital Instruments, Genentech, and Synopsys) mature into established regional firms. In addition, of course, the characteristics of the spin-off firms, especially their role as sources of still other new firms, is another important influence on the contrasting trajectories of university-based regional growth in Los Angeles, Santa Barbara, San Diego, and the San Francisco Bay Area, as the chapters suggest.[8] This influence of established and new firms is but one example of the ways in which the effects of university research on industrial innovation and regional growth are affected by institutions external to the university. Among the most important of these, in addition to the characteristics of existing firms, is the extent to which labor markets for scientists and engineers support movement in both directions between academic and industry and the characteristics of financial markets, notably the supply of venture capital and strength of "angel investor" networks.

Our cases also show that the contributions of university research to regional growth and those of regional industry to university research can change over time, although university-trained personnel appear to be important sources of linkage and benefit throughout the development of all of the industrial clusters examined in this volume. During the growth of the Napa Valley wine industry in the 1950s and 1960s, for example, UC Davis was the primary source of advice and technical information for the regional industry. As the technical capabilities of the Napa Valley winemakers grew, however, the importance of UCD research diminished somewhat relative to that of UC enology and viticulture graduates. By contrast, UCSD research results were of modest importance in the establishment of Linkabit and its successor, Qualcomm, in the San Diego region. Instead, the university's graduates were an important source of benefit for regional industry, a benefit that was supplemented by the contributions of UCSD University Extension courses. The expansion of the regional wireless communications cluster in San Diego, however, relied to a growing extent on the contributions of UCSD research.

Even in biotechnology, where the central role of basic science means that the knowledge underpinning industrial innovations is more likely to flow from academia to industry, numerous industry-based technical advances have been of major significance for academic as well as industrial research. For example, the polymerase chain reaction technology (itself the basis for a Nobel Prize in 1993) was invented by Cetus scientists and rapidly put to use in both academia and industry.

Casper's Chapter Three also highlights another type of knowledge-based interaction that involves contributions from practitioners to laboratory research. William Rutter, who was hired as the chairman of the Department of Biochemistry and Biophysics at UCSF in 1968, encouraged faculty members to collaborate with clinicians in their research, thereby linking the medical practitioner community with laboratory scientists. Casper also presents data on the extent of coauthorship between Genentech and scientists at both UCSF and Stanford: "Genentech scientists were authors on 6,847 publications, of which 539 included collaborations with UCSF scientists, in addition to 267 collaborations with Stanford researchers and 57 with UC Berkeley." In the San Francisco Bay Area, collaboration between local universities and small biotechnology firms continued long after the firms had grown to significant size. San Diego biotechnology firms, however, relied less on scientific publications coauthored with university researchers in their efforts to commercialize university-developed innovations. Even in this “science-based” field of research, then, Casper’s chapter and other published research highlight the limits of a naïve “linear model” conceptualization of the links between university research and industrial innovation.

Another important source of benefit for universities from regional industry is the financial contributions of firms to university research, in the form of philanthropic contributions and industry-sponsored research. The chapters describe the ways in which the beneficiaries of university technology transfer may also support the university through philanthropy, which assumes a number of forms. At UCB, regional and national semiconductor firms provided significant funds for an expansion of the building that houses the Electrical Engineering and Computer Science Department. The founder of Digital Instruments has made a number of significant philanthropic contributions to UCSB; Irwin Jacobs, the founder of Qualcomm, has made major philanthropic contributions to UCSD; and Robert Mondavi (a Stanford graduate) funded the establishment of the Robert Mondavi Institute for Wine and Food Science at UC Davis. Industry-sponsored research is also very significant, especially by comparison with licensing revenues. Annual gross licensing revenues for the UC system (including awards from successful patent litigation) averaged roughly $99 million during fiscal years (FY) 1999 through 2004, less than one-half of industry-sponsored research for the UC system in FY 2003 (a total of $235 million).[9]

Our chapters illustrate the complex ways within which universities or, put more properly, university researchers contribute to the industrial technological advancement. They support a position of cautious skepticism in assessing the value of the “patent-based approach” to knowledge and technology transfer that received a significant impetus from the Bayh-Dole Act of 1980.[10] Patents and licensing assuredly are important in some fields and far less so in others. Moreover, an exclusive focus on patent-based channels of technology transfer may inadvertently lead to policies that discourage other equally beneficial or valuable (for both industry and academia) channels of interaction. The interactive relationship between regional industry and the development of university research must be kept in mind by both university and industrial managers in developing policies to maximize mutual benefit from these relationships.

We believe that these chapters provide a rich portrait of the ways in which a nationally unique public university system, the University of California, has operated as a powerful engine for knowledge-based growth throughout this large and diverse state. Although our chapters omit other important instances of knowledge-based interactions between UC and industry researchers, we believe that the emphasis in these chapters on the numerous, diverse, and heterogeneous channels of interaction between UC campuses and regional industry would only be reinforced by a lengthier study. Moreover, these chapters scarcely touch on other crucial contributions of the UC campuses to state and national economic welfare through the sheer breadth and excellence of the training provided on these campuses, as well as the equally essential contributions of this training to economic and social mobility within a diverse and expanding state population. From a social and economic policy perspective, it is essential to recognize the importance of these broader contributions from the UC system to the national and regional economies. California's future economic success depends on knowledge-based growth, something to which the University of California system must remain an indispensable contributor.

NOTES

1. For an industry insider's view on the relationship between industry and the university in semiconductors, see Moore and Davis (2002).

2. [James] Gibbons [future dean of engineering at Stanford], a junior faculty in the Electrical Engineering Department [*sic*] at Stanford, worked at Shockley Semiconductor on a part-time basis. Frederick Terman, Stanford's provost, and John Linvill, the head of the Solid-State Laboratory, had recently apprenticed Gibbons to William Shockley. They had asked Gibbons to learn the techniques required for the fabrication of silicon devices from Shockley and then transfer these techniques back to the university (Lecuyer, 2005a, p. 138).

3. According to the National Science Board (2012), public universities "represented less than 10 percent of all 4-year colleges and universities in the U.S. in 2009, but about 33 percent of first-time, full-time undergraduate enrollment that year" (p. 3). In addition, public universities enroll a disproportionate share of undergraduates from low-income backgrounds; 30 percent of Pell grant recipients attended public universities in the 2009–2010 academic year, well above the 13 percent of grant recipients enrolling at private, nonprofit four-year institutions (National Science Board, 2012).

4. Shanghai Jiaotong University, 2012.

5. For further confirmation of this point, see Owen-Smith and Powell (2006).

6. For another case study of the interaction between university researchers and a university spin-off that commercialized a scientific instrument technology, see Lenoir and Lécuyer (1995) on the commercialization of Stanford-pioneered nuclear magnetic resonance technology at Varian.

7. Rosenberg and Nelson (1994) highlighted the contributions to industrial innovation of applied research in U.S. universities in their important 1994 paper.

8. The late Steven Klepper (2011) pointed out that such entrepreneurial spawning of new from established firms frequently is responsible for the formation of an industrial cluster.

9. *Net* licensing revenues for the UC system (which nets out royalty payments to faculty inventors) were of course far smaller, averaging slightly less than $22 million annually during this period. More recent data on net revenues unfortunately are unavailable.

10. For one skeptical view, see Kenney and Patton (2009, 2011).