Research & Occasional Paper Series: CSHE.6.02

UNIVERSITY OF CALIFORNIA, BERKELEY
http://ishi.lib.berkeley.edu/cshe/

THE ROLE AND EXPERIENCE OF INVENTORS AND START-UPS IN COMMERCIALIZING UNIVERSITY RESEARCH: CASE STUDIES AT THE UNIVERSITY OF CALIFORNIA

December 2002

Robert A. Lowe
Graduate School of Industrial Administration
Carnegie Mellon University
Tech and Frew Streets
Pittsburgh, PA 15213
roblowe@andrew.cmu.edu

ABSTRACT
This chapter from the author's dissertation summarizes findings from case studies of university-based start-up firms. The case studies contribute descriptive accounts to support and illuminate emerging empirical research on this specialized set of start-ups. The case studies highlight several interesting findings related to the special role of inventors and the university in developing the technology as well as how the operating experience of these firms compares and contrasts with standard beliefs about start-ups. For example, the case studies document the stark contrasts among university-based start-ups with respect to both the importance of intellectual property and the company's ability to access venture capital. The case studies also highlight the importance of the inventor's personal (or tacit) knowledge in developing the technology. Finally, university inventions in the electronics and semiconductor fields, unlike pharmaceuticals and biotechnology, were the result of research that had been conducted years earlier in corporate laboratories. Hence, technology was transferred into the university.

1 Introduction

Firms founded on university inventions have been an important, and often controversial, feature of the U.S. national innovation system. Although the majority of previous research on universities has focused primarily on patenting and licensing activity in a broad sense, recently several scholars have highlighted the active role that small and new firms play in commercializing inventions discovered at American universities (e.g. Roberts 1991; Lerner 1999; Rosenberg 2000). Hewlett-Packard provides a classic example of a firm founded on one of the founder's graduate school work. Moreover, the roster of university-based start-ups in

California's high technology corridors includes several other notable firms, such as Genentech and Chiron in biotechnology and Google and Inktomi in software.

Despite the apparent economic and technological contribution of university-based start-ups, these firms have also been controversial. University-industry relations have generally attracted critical scrutiny in the press, particularly with respect to university patenting and licensing operations which have flourished since the passage of the Bayh-Dole Act (Press and Washburn 2000). Concerns over faculty-founded firms have sparked many universities to issue policies governing faculty and student interaction outside of the classroom. The University of California (UC), for example, maintains standing committees on conflict-of-interest, whose activities include reviews of faculty-founded firms for such conflicts.

Nonetheless, such start-ups are an important vehicle for moving technology out of the university lab and into commercial development, and university patenting and licensing offices have taken note of the growing number of inventors who license their own inventions from the university to found firms. As Harvard Medical School's technology licensing policy reads:

> An emerging company may offer the best opportunity for the rapid commercial development of at least some Harvard inventions.… Therefore, when an emerging company is deemed to have the potential of obtaining sufficient financial and management resources to be capable of vigorous development of University technology, licensing to that company should be given serious consideration. Furthermore, (the licensing office) should provide reasonable assistance to the faculty members involved as they seek to launch the new company by identifying potential sources of financing and providing input on draft business plans.

This attention to start-ups is well-founded: start-ups account for nearly one-quarter of the licensees at UC. The majority of these licenses are to faculty and graduate students licensing their own inventions back from the university to found firms.

This chapter summarizes case studies on "university licensee start-ups" at the University of California's nine-campus system. These start-ups were founded by an inventor to commercialize his or her invention. For firms founded by an inventor, the inventor licensed his or her invention from the university because UC maintains title to any discovery made by a researcher – be they faculty, graduate student, or post-doc – while the researcher is an employee of the university.

This area of research is still emerging, and unfortunately evidence and analysis has not kept pace with policy decisions. The primary goal of this chapter is to contribute much needed evidence and analysis regarding university licensing and inventor-founded firms. At a basic level, the main contribution of this chapter is to document the experiences and circumstances surrounding the formation of this special sample of start-ups. In doing so, I focus on how and why university licensee start-ups are founded, and what characteristics – technological, economic, or otherwise differentiate these start-ups from other high technology firms. In the context of this dissertation, the evidence in this chapter provides a foundation for the theory and analysis in Chapters 3 and 4.

For public policy, these case studies shed light on the relative impact of commonly recognized drivers of entrepreneurship, such as intellectual property protection and venture capital. This chapter also contributes to a growing number of case studies at other universities to describe the university technology transfer process – that is, the process of moving inventions out of university laboratories for development and commercialization (Colyvas, *et al*. 2002).

Four general themes emerged from the case studies. First, in support of recent survey results reported by Jensen and Thursby (2001), the start-ups were founded to develop inventions that were at an early-stage (pre-prototype) of development. These inventions were characterized by considerable technological uncertainty, which deterred established firms from initially licensing and venture capital from making substantial investments during the early years of each firm. In response, the inventors sought federal research grants for initial funding and were later able to secure the interest of private equity and established firms.

Second, the inventor's experience and personal knowledge gained from working with the invention proved to be invaluable for a number of firms. Several scholars have recently highlighted the importance of transferring inventor knowledge in a licensing transaction (Arora 1995; Arora 1996; Agrawal 2000). The case studies provide descriptive accounts to support this research.

Third, although the inventions were at this early stage of development, the underlying research had been progressing for a number of years and in some cases decades. In several cases, particularly those start-ups founded by engineering faculty, the underlying research was begun in corporate laboratories decades earlier and moved to the University of California labs as scientists in the corporate labs accepted faculty appointments. Thus, technology transfer flowed into the university.

Finally, by definition the university played an important role in each of these start-ups' histories. However, the exact nature of this role differs dramatically across the firms. For example, intellectual property appears to play an important role for some firms, particularly in the biomedical sciences, but appeared to be of less importance for other types of firms. Instead, the inventor's personal, or "tacit," knowledge was an effective means to appropriate rents from the invention.

Indeed, one of the primary themes underlying this chapter is that the effectiveness of intellectual property, venture capital, and other alleged drivers of entrepreneurship – at least in the university setting – are so specific to the industry and state of licensed technology, that any broad policy conclusions need to further account for these specific characteristics. This statement does not imply that we cannot find specific economic or sociological mechanisms at work. Rather, one of the main challenges in setting intellectual property, public funding, and other such policies is to account for important industry and technology differences.

Although case studies provide rich description, any "findings" are of course subject to challenge based on how generalizable they are. This problem can partially be addressed by carefully selecting the firms or inventions to study. In the next section, I describe my research methodology with specific attention to my case selection strategy: choosing a sample of cases that are closely representative of the larger population. I also assess the advantages and limitations of focusing on UC's technology transfer activities. Section 3 summarizes general themes that emerged from the case studies. Section 4 presents four case studies of university licensee start-ups to illustrate these themes. Section 5 concludes with a discussion of further research opportunities and open questions in this field.

2 Research Questions and Methodology

Although case studies allow for detailed investigation, they are limited in several ways. Such research is rarely generalizable because results are often overdetermined: very few observations are used to explain phenomena that result from a multitude of factors. The methodology can also be constructed to highlight only particular findings via narrow research questions and particular sample selection strategies. In summary, one must always worry about sound methodology, but case studies in particular leave abundant opportunity for seeking answers under the proverbial lamppost.

In this section, I first summarize the broad research questions addressed in this chapter. Since a discussion of methodology requires knowledge of the institutional environments to provide a frame of reference, I next highlight the advantages and limitations of studying the University of California in this context. Finally, I focus on the sample selection strategy employed to assuage the above concerns

2.1 Research Questions

The field research presented in this chapter represents an effort to describe the experiences of start-up firms in both licensing intellectual property from a university and in building a company during the initial stages of product development. The latter issue is particularly important in the university-licensing context because many university inventions are patented and licensed while still several years from even a working prototype or commercial product (Jensen and Thursby 2001). As the case studies reveal, start-ups are especially likely to license technologies that are early stage and carry significant technological uncertainty.

I addressed three broad areas in my field research. These areas guided my background research as well as interviews with the firms' principals:

1. Technology history and the role of the start-up: When and where was the core technology invented? Why was a new firm founded to commercialize the technology? What was the role of established firms in developing the technology or in the firm's formation?

2. Financial history: How are such firms funded? How do the firm's funding sources and goals change as the technology is developed?

3. Intellectual property: How important were patents in the founding and continued development of the firm? How important were other methods of appropriability?

2.2 Advantages and limitations of studying start-ups at the University of California

The University of California affords at least two advantages for studying technology transfer in general and start-up activity in particular. First, the nine-campus UC system is the largest technology transfer program among U.S. universities, both in terms of the number of utility patents granted and total licensing revenue (Zacks 2000). For some perspective on the size of patenting and licensing operations at UC, consider the following. UC was granted 468 U.S. patents in 1999; this is roughly the same number of patents as the next four most active patenting universities combined and triple that of the second most active patenting university, MIT (151 patents) (Zacks 2000). UC reported $73.1 million in gross licensing income in 1999, although the income difference between UC and other universities is much less dramatic than the difference in number of patents. UC's licensing income is not three times that of the second largest licenser, Columbia University ($61.6 million), because unlike UC, Columbia and several of the largest universities in terms of licensing income rely on one or two patents that generate substantial income. Indeed, in 1999 three of the top five universities in terms of licensing revenue- Columbia, Florida State, and Yale- were not in the top 10 universities in number of patents received.

Second, since UC has nine campuses, a broader spectrum of technologies can be compared, including inventions from a variety of departments and several medical and engineering schools. This broad spectrum contrasts with most single campus universities that do not have significant patenting operations in each of engineering, biomedical (including biotechnology, pharmaceuticals, and medical devices), and software, for example.

UC is also one of the oldest technology transfer operations among U.S. institutions, and findings reported herein reflect those of an experienced player in the patenting and licensing game (see Mowery, et al. 2001 for a more complete history of UC's patenting and licensing operations). UC has long maintained policies regarding the rights of inventors. UC maintains first rights to title of any patentable invention by a faculty or graduate student employed by the university[1]. Effectively, faculty and graduate students employed by the University, even if temporarily, are contractually obligated to disclose findings from any activities that they believe are patentable. This policy is broader in scope than the requirements set forth by the Bayh-Dole Act, which established the intellectual property policy for most universities.

Its important to note that the inventions licensed by inventor-founded start-ups in the population sampled for this chapter were all reviewed by established firms prior to the inventor licensing his or her invention. Historically, as part of University of California policy, even when inventors seek to start a firm, one of more established firms had the opportunity to license. Established firms were able to review inventions through several mechanisms. Established firms often reviewed inventions at minimal or no cost through Secrecy Agreements prior to signing an option or license. Established firms also reviewed the invention as part of a funding contract. In a few cases, the review by an established firm is documented in discussions with the licensing officers or inventor and maintained on file at the OTT.

The decision to license is of course based on both the scientific value of the invention as well as the value of intellectual property on the invention. Thus, UC inventors in theory reveal the basics of an invention to an established firm prior to any licensing agreements. This practice reduces the problem of adverse selection at UC, whereby inventors would keep the best inventions for themselves and license "low quality" findings. Inventors could act strategically and misrepresent the invention in their dealings with licensing officers and established firms, but this action is buffered the fact that the inventors have ongoing relationships with both licensing officers and companies.

UC's long history of licensing and sheer scale in operations reduces its comparability with other individual institutions. Such differences primarily affect areas where experience or path-dependent institutional rules and practices influence activities. For the findings of this study, such activities include managing licenses to start-up firms (to the extent that such licenses present challenges beyond licenses to established firms) and faculty's decisions to disclose inventions and to found companies. For example, during the 1990's UC faculty may

---

[1] UC's domain of control does not formally include copyrights, for example. However, in recent years a number of inventors at the Berkeley and San Diego campuses have turned to the university to manage licensing of their copyrighted software.

hypothetically be more comfortable founding firms than were faculty at a university with little previous technology transfer activity because the UC faculty benefit from the experience of their colleagues and Licensing Officers. Although the analysis below does not shed light on whether such differences are important, they should be kept in mind as potential limitations.

2.3 Field Research Methodology

Sample Selection

Several selection strategies exist, including success stories, representative samples, random choices, and matched success-failure cases. Since this research strives to paint a descriptive picture of start-ups' experiences, cases were systematically chosen to be representative of the larger sample. Selection was based on three dimensions: technology field, founders' backgrounds, and geographic location.

Research began with a database of 106 licensee start-ups identified by the University of California's Office of Technology Transfer (OTT). This office is responsible for managing the patenting and licensing of inventions discovered at the University of California and has constructed this database as an ongoing effort to monitor the evolution of all UC licensee start-ups. Start-ups, in this context, are defined as firms founded on a contractual agreement, such as an option or a license, regarding intellectual property for which the university maintains title.

It should be noted that there are several types of contractual agreements related to licensing intellectual property that these firms can enter into. For this chapter, I focus on licenses and options, although I will also discuss a Letter-of-Intent (LOI) case, as well. Options are agreements that give rights to the outside party to a future licensing agreement in exchange for a moderate payment. The options specify whether the ensuing license would be exclusive to the licensee or field-of-use exclusive (e.g. for use in only certain, specified applications) in the contract. An LOI is similar to an option, but is limited to a short term (less than one year), requires smaller up-front payments, and is granted primarily in engineering fields. Upon signing an LOI, OTT takes the invention "off the market" for a short term until either the technology is licensed or the contract expires. Options and LOI agreements are particularly attractive for start-ups to secure future rights to a technology for a smaller cash payment, while seeking funding and continuing to develop the technology. Firms do not have to enter options or LOI's prior to signing a license for a technology.

Licensing agreements between the university and a firm can be exclusive, non-exclusive, and field-of-use licenses. Typically, an up-front fixed fee plus a royalty stream based on product sales is paid by the licensee to the university, with a portion paid back to the inventor. Since the late 1990's, the University has been more willing to accept equity in exchange for the up-front payments for start-ups and small firms, although this has been a point of controversy.

Of the 106 firms identified to be founded on UC technology between 1980 and 1999, I selected 12 firms as representative of the population to participate in case studies. Figure 1 depicts the distribution of start-ups by technology area and campus where the technology was invented. Two of the twelve companies declined participation, Companies C and D in the Figure.

As illustrated in Figure 1, the majority of licensed inventions at UC are in three general technology classes, health-related (biotechnology, pharmaceuticals, and medical devices), engineering applications (excluding medical devices), and software. Engineering applications includes photonics and lasers, computer hardware, and advanced materials. As widely reported, biotechnology and pharmaceuticals dominate university patenting and licensing activities, and these areas also account for the majority of start-ups. The exact reasons for this distribution of technologies developed by start-ups, however, are not clear. On the one hand, pharmaceuticals and biotechnology rely heavily on product innovation, and Figure 1 may illustrate the particular importance of innovation (generally or at the university) to these industries. On the other hand, this distribution may also represent the notion that patents are less important than other factors to founding firms or developing technologies in a variety of engineering fields. Indeed, the first case study discussed below supports this possibility.

Start-ups were also selected for the case studies to roughly mirror the distribution of inventions across campuses. Note that some inventions have multiple inventors from different campuses. Each campus in a multi-campus invention is given credit for the invention. Berkeley by far produced the most start-ups, despite there being no medical school on Berkeley's campus. Note that the campus of invention is highly correlated with the technology class. For example, a significant portion of the licensee start-ups from Santa Barbara were founded by faculty at UCSB's engineering school. Given UC-San Francisco's medical center, UC-San Francisco faculty primarily founded medical device and biotechnology firms.

Case Study Process

Once the case study subjects were identified, interviews served as the principal source of data collection, and were conducted with participating companies between July 2000 and October 2001. Initial interviews were on-site at each company with founders and CEO's. Although a structured set of questions were used to address the above research issues, interviews were conducted as open discussions. When possible, additional interviews were conducted with current employees. Follow-up interviews were conducted in person and via telephone. During this process, Licensing Officers and others familiar with the original license transaction at the University of California were interviewed. This latter set of interviews was conducted to corroborate and supplement the data gathered during prior research and interviews with companies.

Background information on inventions, industry, and inventors was collected from records at OTT and secondary sources.

3 General Themes

This section highlights four general themes that emerged from the case studies:

1. Inventor-founded firms tended to license inventions associated with considerable technological uncertainty

2. Inventor's personal knowledge and experience was seen as at least as important as the intellectual property rights to further developing inventions.

3. Several inventions had been investigated for decades and the university research and start-ups were actually in the middle of a long research trajectory rather than at the front end.

4. The university often plays an important role in assisting inventor-founded start-ups, but the nature of the university's role differs substantially across technology classes.

3.1 Inventor-founded start-ups and technological uncertainty

Survey results reported by Jensen and Thursby (2001) illustrate that a substantial portion of university inventions are at an early stage of development – often inventions do not have a working prototype – at the time when firms negotiate a license. Such inventions may require two or more years of further development before a commercial product will emerge. For established firms trying to license such early-stage inventions, there is considerable uncertainty over the feasibility of an invention. That is, these firms must consider whether an idea that looks good on chapter can really be developed and ultimately commercialized. This "technological uncertainty" can deter established firms from licensing early-stage inventions.

One of the main findings from my case studies is that inventors founded firms to further develop inventions that were several years away from full development. Several firms profiled, such as Calimetrics and Cortex, spent five years or more in development. Other companies, such as Nitres and Neomorphic, drastically altered fundamental characteristics of the original invention in developing a commercial-scale product.

In several cases, established firms expressed interest in licensing the technology at the time it was disclosed to the University. For example, at Calimetrics the inventors introduced an established firm that had been supplying their Berkeley laboratory with equipment to the UC-Berkeley licensing office. The established firm expressed considerable interest in the technology and signed a license agreement in 1992. However, after a year, the established firm abandoned the research. A few years later, two firms were founded among the members of the inventing team: Calimetrics was founded by the graduate students that worked on the invention and Quadrant Imaging was founded by the supervising faculty member[2].

Calimetrics spent five years developing and refining the technology before the first commercial products were released. Pangenix' invention was reviewed by a number of biotechnology firms with various applications in mind, but no licenses were negotiated by the biotechnology firms until years later when one of the Pangenix inventors was hired away by one of the interested biotechs.

Technological uncertainty also played out in the financial markets. A new firm must in most cases acquire significant financing to pay for laboratory equipment, office space, and staff. In spite of the abundance of venture capital (VC) money in California during the 1990's – when all but one of the case studies was founded, most of the start-ups were not able to attract significant VC money until several years after their founding. These firms instead relied on alternative sources of funding.

Nitres, Calimetrics, and Neomorphic, for example, were funded primarily by government grants during the initial years. These firms received money from the National Institute of Standards and Technology's (NIST) Advanced Technology Program (ATP) and the Small Business Innovation Research (SBIR) program: programs designed to fund early stage technologies and small firms. This funding was supplemented by corporate sponsorship. As one

[2] The faculty member and founder of Quadrant Imaging unfortunately passed away soon after founding the firm. The firm then closed without further development effort.

entrepreneur recalled, "Our technology was early-stage. We could only describe where we were going, but we didn't have any prototype to show [venture capitalists]. They want to see that you're going to have a product soon."

These funding histories suggest several important lessons and opportunities for research. First, many studies of new firms and entrepreneurship focus on the role of venture capital. This stream of research has proven both interesting and fruitful. However, for early-stage technologies, venture capital markets may not be a viable source of funds, given the uncertainty and long time horizon for economic returns to the invention (Bhide 2000). Rather, venture capital firms often provide a second source of funding after technology is well-developed. These findings corroborate work by Lerner (1999) and others who have suggested that venture capital investors may shy away from start-ups developing early-stage technologies. Indeed, this was one of the key arguments for the creation of the SBIR program (Lerner 1999).

Secondly, these findings highlight the need to further understand and assess the impact of federal funding programs on the incentives for new firm formation and technological development. Some research is already under way on this topic (Gans and Stern 2000; Lerner 1999). Moreover, during the 1990's European countries have developed government-sponsored venture funds to varying degrees of limited success (for example, see Giesecke 2000). Therefore, this contrast only underscores the need to understand, generally, the impact of federal-funding programs for new firms and new technologies.

University equity involvement with companies has attracted considerable, and sometimes contentious, discussion. To the extent that start-ups need to license rights to their founders' inventions held in title by the University, equity stakes may be the only feasible exchange that a cash-strapped start-up can offer for initial payments. Additionally, to the extent that start-ups may be the only interested or feasible licensees for some inventions, university equity, or at least a waiver of up-front licensing fees, may be necessary for universities to successfully license such technologies.

3.2 The Importance of Inventor Knowledge and Experience

In a number of cases, the inventor played a particularly important role in developing the technology. As indicated in several case studies below, the critical, valuable asset needed to further develop the invention was the inventor's personal or "tacit" knowledge. Originally characterized by Michael Polanyi (1958), tacit knowledge refers to knowledge that cannot be easily written down or transferred among scientists, but can only be transferred through personal interaction and experience.

Unlike other broad themes in this chapter, the importance of inventor knowledge is not specific to any one technology field. Among the cases detailed below, Pangenix and Xenometrix, both biotechnology firms, developed technology for which the inventor's accumulated experience was necessary to work with the technology on a day-to-day basis. Consistent with Polanyi's original description of tacit knowledge, knowledge transfer took place through apprenticeship training: both companies employed full time a scientist who was trained by the inventors over several months to replicate the research and work with the technology. Both principal inventors also indicated that customers regularly have considerable difficulty in replicating the invention or further developing the invention without regular discussions and interaction with the inventors.

Founders of the semiconductor firm Nitres also stressed the importance of personal knowledge, and in particular their graduate students' amassed experience in working with the invention over several years, for the company's scientific progress. This is a claim often made by scientists in semiconductors working with new materials.

3.3 The Role of Start-ups: Often the middle of a long technological path

Although the inventions licensed by inventor-founded start-ups were years away from commercial development, many of these inventions were also the result of decades of research. A number of inventor-founded start-ups licensed inventions rooted in an older scientific base, as compared to inventions licensed by established firms. Consider a proxy of the age of invention A's underlying science, or "scientific base," as the average age of patents cited by invention A's patent(s). For patented inventions discovered at UC between 1986 and 1995, the average age of science base, using this measure, was 8.4 years for technologies licensed by start-ups. This compares with an average citation age of 7.3 years for technologies licensed by established firms. Regression results reported in Chapter 3 support this finding: even after controlling for invention year, the patent's technology class, and other variables, the probability that a start-up licenses a UC patent – conditional on that patent being licensed – is (weakly) positively correlated with the age of the patent's citations. Such data contradicts conventional wisdom that start-ups develop technologies based on "newer" research than do established firms.

The case studies shed light on why some start-ups appear to license inventions with an older scientific base. For several start-ups, particularly those founded by engineering faculty, the underlying technology had been studied in corporate research labs decades earlier. Nitres, founded in the mid-1990's, was founded to commercialize technologies based on gallium nitride (GaN), a semiconductor that had been studied since the early 1970's at both universities and major corporate labs such as RCA and Matsushita. Agility Communications was founded to develop technology that the inventor began working on while he was at Bell Labs over a decade earlier.

Biotechnology firm Xenometrix licensed assays based on previous technology that had been widely used to test for mutagenic and carcinogenic properties in the pharmaceutical, chemical, and foods industries for over 20 years. Consistent with the measure of age of the underlying scientific base discussed above, Xenometrix' average citation age is 15.6 years, double that of all UC licensees and triple that of other UC patents in the same International Patent Classification class (biochemistry, microbiology and genetic engineering patents).

3.4 Technology Transfer: The role of the university

It has long been recognized in the economics of science literature that the invention-innovation process is characterized by a feedback loop, rather than the linear model discussed by Vannevar Bush. The feedback loop model portrays the research process as iterative: a give-and-take between university research teams and corporate labs. However, universities are typically assumed to be the wellspring in the process.

Several of the start-ups exhibit a different notion, and one that complements the first theme mentioned above: a number of inventors founded firms to develop technology that had long been researched, though undeveloped, at corporate labs. This point applies almost exclusively to the firms founded by engineering faculty. The case studies illustrate that the university's role in the broader scientific effort differs considerably among biomedical and other technology fields.

Nitres illustrates a research path on which the university was a follower of early corporate lab research efforts on fundamental technologies. The three pioneers in gallium nitride, Nitres' core technology, worked on gallium-based and similar semiconductors in company labs for years before taking positions at a university. Credited as the founder of research on GaN-based semiconductors, Jacques Pankove worked for RCA while starting research in this field. Prior to working on gallium nitride at Nagoya University, Isamu Akasaki spent 17 years at Matsushita Research Institute researching gallium-based semiconductors. The other GaN pioneer, Shuji Nakamura, made his primary contributions to the field while working at Nichia Chemical and only years later moved to UC- Santa Barbara.

Early-stage research at Bell Labs and its successor, Bellcore, also followed researchers as they took faculty positions at UC. This research led to several UC inventor-founded firms in optoelectronics, including Agility Communications and Optical Concepts – both by UC Santa Barbara Professor Larry Coldren – and Bandwidth9, among others. As Coldren characterized the founding of Agility, which was incorporated in October 1998, "My work started, and you could say Agility started, in a vague sense, in the very early 1980's, probably even 1979... at Bell Labs" (Coldren 2002).

Two points are raised by these examples. First, these examples support the previous theme: inventor-founded firms tended to license technologies based on an older scientific base. These examples highlight research that had been underway at corporate labs for years and sometimes decades, but was never completed.

Second, these examples provide further evidence that research efforts include considerable feedback between universities and industry. In addition, these cases suggest a more interesting process: technology transfer into the university from corporations. The mechanism behind this transfer is primarily the flow of researchers, common in engineering disciplines, who leave work in firms' basic research labs for faculty positions.

This characterization differs substantially from academic and popular discussion of the university's role in advancing technology. Part of the reason for this difference is that research and attention to university-industry relationships and university technology transfer has historically focused on biotechnology and pharmaceuticals at the exclusion of other fields. While these two general fields do account for most of university patenting and licensing activity at UC and other universities (Mowery, et al. 2001), there is a substantial portion of university research, although comparatively less patenting and licensing, in engineering fields. Moreover, studies often focus on a patent or license as the unit of analysis, rather than considering the history of the technology.

The problem of focusing on biotechnology and pharmaceuticals relates to another theme among the case studies: the importance of university intellectual property. This is perhaps the most important issue addressed in this chapter given that university and national policies have been crafted on the belief that intellectual property is essential for start-ups to develop and commercialize technologies. Indeed, the Bayh-Dole Act recognized the importance of intellectual property rights specifically for small firms and universities participating in federally-sponsored research (Eisenberg:1996). Was university intellectual property important in the decision to start a firm? The answer is a resounding "Sometimes."

Cortex Pharmaceuticals, cofounded by a UC-Irvine professor of psychobiology, has licensed from UC or been granted 14 patents, with others pending. The firm has a long history of secrecy, option, and licensing agreements with the University that continues even 15 years after the firm's founding. Xenometrix engaged in a legal dispute with Harvard University over maintaining exclusive rights to intellectual property licensed by the firm. As the Xenometrix CEO described, "You want the IP there since it's the only tangible evidence you have in court" (Gee 2001). Clearly, in some cases intellectual property plays an important role in the start-up's development.

However, other technologies, namely those outside biomedical, illustrate a different story. After securing an LOI agreement, one firm never followed through on any licenses. Instead, the firm's scientists chose to continue their own research, and the have received patents on the in-house research. The founder of another company confided that the intellectual property did not actually cover the company's current technology because the company's core technology had evolved so much so as to not be covered by the original license (or any other existing intellectual property), "but we pay the university anyway to keep everyone happy." Both companies made some investment in pursuing a license, but neither claimed to view the license as a critical piece for founding a firm. The latter company would presumably have pursued new intellectual property or renegotiated the license had they viewed the underlying IP as a valuable asset.

This is not to say that IP rights and university licensing aren't important in an absolute sense in some fields. Indeed, all of the firms profiled do own intellectual property on their inventions, and place resources on managing their IP portfolios.

4 Detailed Case Studies

In this section, I summarize four case studies to describe the general experiences of these companies, with specific focus on the research questions posed in this chapter. As discussed above, several other companies were researched, but are not detailed in this section.

4.1 Nitres

Nitres was founded in 1996 as Widegap Technologies, or WiTech, by two UC- Santa Barbara engineering professors, Steve DenBaars and Umesh Mishra, and an experienced semiconductor executive and entrepreneur, Fred Blum. Nitres, which was acquired by Cree, Inc in May 2000, develops products based on a semiconductor, gallium nitride (GaN), for use in light emitter diodes (LED's), optical sensors, lasers, and wireless applications.

GaN is a wide bandgap semiconductor, meaning that it emits light across a wider spectrum of colors, allowing for colors not previously available from LED's: bright blue and green. GaN emits light at an intensity and spectrum not available from traditional LED materials such as gallium arsenide (GaAs) and silicon (Si). GaN, like other LED's, is more efficient (that is, less energy is lost to heat production in the process of converting electricity to light) than other lighting technologies. In wireless applications, GaN semiconductors also provide greater transmission power with more efficiency than traditional technologies used in mobile phones, military radar, and communications satellites. Note that chemical cousins of GaN based on aluminum and indium have similar properties and are now also used in many of the same applications listed above as a result of the research effort discussed below. Although I focus on GaN, research in this area includes research on a class of related semiconductors that includes these cousins, Class III-V semiconductors.

The history of Nitres and GaN technology illustrates a long and winding research path that included efforts by both public research institutions and corporate labs. GaN was recognized as early as the 1960's for its potential commercial value. However, despite considerable interest in the commercial applications believed possible with GaN LED's, many of the original firms that conducted research on GaN eventually dropped their research programs. This story is marked by the important role of small (Nichia) and new, university-based firms (Cree and Nitres), as well as university labs in continuing research on a technology initially researched in corporate labs. Of particular note is the importance of complementary research and innovations needed to move GaN-based technologies forward.

The history of Nitres also provides insight into the relative importance of intellectual property, and tells a story quite different than that of biotechnology and pharmaceutical firms. To be sure, IP plays an important role at Nitres, but the university patents did not appear necessary to appropriate returns to the technology. Nitres particularly illustrates the importance of keeping inventors, both faculty and graduate students, onboard because their experience and personal knowledge are critical to further developing the technology.

4.1.1 The History of GaN

The original research on GaN first emerged in the late 1960's. Jacques Pankove led the first effort in this field while working at RCA's Princeton labs. Pankove was a successful inventor who had several credits for important discoveries during his career at RCA, including the first transistor that RCA produced commercially. As a result, Pankove had scientific freedom within the company to pursue new areas that might eventually lead to products for RCA.

RCA's Princeton laboratories included considerable activities in basic research, similar to the much larger Bell Labs in this era. As Pankove recalled in an interview, "RCA had a policy of encouraging inventions...There were so many different projects at RCA that it was like a college. You would go to lunch and talk with engineers and pick their brains. You learned a lot there. That was the best atmosphere" for basic research (Pankove 2002).

As part of this philosophy, RCA maintained an apprenticeship training program where young scientists would be assigned to senior researchers who guided their initial research projects. Pankove had been working with gallium arsenide in the late 1960's and assigned a new research apprentice to work with the material, conducting basic tests and measurements. The young scientist began to experiment with different chemicals used to manufacture gallium arsenide. Eventually, and largely by chance, he manufactured a different substance, gallium nitride. With a curious mind, he set to taking basic measurements, but was unable to get an accurate reading for the material's luminescence. Intrigued with the new substance, Pankove set to work testing, measuring, and understanding the material. Pankove soon discovered that the measurement failure for luminescence was due to the fact that GaN's spectrum was outside of that of their test equipment. Indeed, GaN emitted purple and blue light, parts of the spectrum not available from other materials of the day.

Within the tight research community, other scientists began to hear of RCA's work on a blue LED based on GaN. By the mid-1970's, major research companies, such as IBM, Bell Labs, and Matsushita, began research efforts on GaN and related semiconductors in their basic research labs. However, progress on GaN was slow, as it became clear that a number of fundamental advances were needed to realize GaN's potential. After a few years of research on the project, RCA asked Dr. Pankove to discontinue his research in the area. Pankove recalled,

> We had interesting findings, but RCA was not so interested. They didn't think that there would be a project outcome soon enough. They wanted something that was commercial. What can you do with a blue LED? Its interesting to have another color, but what the world really needs is not another color, as much as a cheaper LED. We were using an expensive material. However, I didn't try cheaper substrates since there was so much more research to be done first on GaN.

By the early 1980's, many of these research efforts at other labs were similarly abandoned due to limitations in the materials that could be used for substrates, among other problems (Kahaner 1995). More basic research on new materials for substrates and new crystal growing processes would be necessary to further develop this technology. The decreased interest in GaN coincided with widespread cutbacks and in some case closures of corporate basic research labs. With a long time horizon before GaN would be a commercial product, research on GaN and related materials was seen as a low priority.

However, as GaN projects were being dropped elsewhere, two researchers, Isamu Akasaki and Shuji Nakamura, working independently in Japan quietly pushed forward on the technology. While Akasaki began research first and solved some fundamental problems in GaN research, Nakamura is credited with developing the first GaN LED.

Akasaki first met Pankove in 1972 while Akasaki was visiting RCA's Princeton labs shortly after attending a symposium at the University of Colorado on GaAs and meeting Pankove (Akasaki 1997). At the time, Akasaki was working on another nitride, Aluminum Nitride (AlN). The two scientists met again in 1976 at a symposium in Japan, where they had time to discuss the potential of blue LED's since transportation had been wiped out by a typhoon (Akasaki 1997). Inspired by Pankove's research, Akasaki began work on GaN while at the Matsushita Research Institute in Tokyo. Akasaki submitted his two initial project proposals for funding by the Ministry of International Trade and Industry (MITI), recognizing that his "company was unlikely to fully fund such risky research" (Sandhu 1998). After several years working on GaN in his corporate lab, Akasaki moved to Nagoya University in 1981 to continue his research, bringing the research he had started at Matsushita into the University.

At about the same time, Shuji Nakamura, a researcher at a small Japanese maker of phosphors for cathode-ray tubes and fluorescent lighting – Nichia Chemical – became interested in GaN after working on a series of related research projects. Nakamura joined Nichia in 1980 after completing a master's degree in electrical engineering at nearby University of Tokushima. One of his first tasks at Nichia was to develop gallium phosphide crystals, which emit red and yellow-green light, for sale to manufacturers of LED devices. As the lone scientist on the project, Nakamura managed every part of the process, including building equipment, growing and working with crystals, and cleaning up after regular laboratory explosions. Nakamura spent three years on the project until finally he could grow crystals for commercial use. Although the research succeeded, sales were low as the company competed directly with larger Japanese firms (Zorpette 2000).

Nakamura then turned to working on gallium arsenide crystals, and Nichia eventually began manufacturing complete LED's rather than only the crystals. Nakamura was able to produce GaAs crystals. However, GaAs was a relatively familiar material and had been researched as a semiconductor for LED's by many of the larger firms in the industry. As had been the case on Nakamura's first project, Nichia struggled to compete with larger firms on sales (Zorpette, 2000).

Nakamura initiated his next research project, on GaN, against the advice of others at Nichia. In a published interview, Nakamura recalled that his new research agenda was based on the premise that a small firm could only compete in the market if it produced niche products that large firms were not commercializing (Zorpette 2000). Still working alone, the Nichia scientist began research on GaN while the larger research firms and several universities were pursuing another group of semiconductors, such as zinc selenide, that also held the promise of a blue LED. These other materials were similar in structure to GaAs and were believed to be more feasible to produce. However, researchers in corporate labs and at a handful of U.S. universities could never produce these LED's to last longer than a few hundred hours, making them impractical for commercial use. Nakamura took a leave of absence to study at the University of Florida, spending 10 months building the necessary equipment before returning to Nichia to begin to his GaN research (Zorpette 2000).

Nakamura improved on Akasaki's research with better crystal growth methods. Moreover, one of Nakamura's most substantial contributions was to modify the standard equipment used in crystal growth, drawing from his experiences building equipment at Nichia and later at the University of Florida. During 1990-1991, Nakamura's research process was to modify the equipment each morning, then grow several crystal samples in the afternoon, and compare results with previous days (Zorpette 2000). This research process was primarily one of trial-and-error, comparing equipment and process modifications to output until he produced bright blue and green GaN-based LED's. After two decades of research, the culmination of multiple, significant innovations in production processes, materials substrates, and equipment finally made GaN appear commercially feasible.

By the end of the decade, other researchers regained interest in GaN as discoveries by Akasaki and Nakamura were patented. Patents during the early 1990's were granted to researchers at Nichia, Akasaki's Nagoya University, and a new firm, Cree Research. Cree, founded in 1987 with patents from North Carolina State University, was a small firm conducting research on silicon carbide material for wafers and electronic devices. After early successes in that area, Cree later began a research program to improve its crystal growth and manufacturing processes, and received some of the first patents during the resurgence of interest in GaN fueled by Akasaki's and Nakamura's advances. Although Cree itself was at one time a university start-up and a young firm when starting research on GaN, Cree was a 13-year-old, public company with a product portfolio including semiconductor materials and final goods by the time it acquired Nitres.

Nonetheless, by this time Nakamura had a substantial technological lead, and produced the first prototype GaN blue LED in his lab in 1994, beating out major research companies and several universities that by now had begun active GaN research efforts. Figure 2 illustrates the patenting history for GaN. As demonstrated in this figure, early patents were assigned to corporate labs. During the 1980's, the few issued patents reflect a mix of university research (Prof. Akasaki at Nagoya University) and research at a small firm, Nichia Chemical. Finally in the early 1990's, corporations and universities became dually active in patenting GaN-related innovations.

Interestingly, beyond Akasaki's inventions, the other university-assigned inventions during the 1980's were filed by Jacques Pankove, who had moved to the University of Colorado from RCA. Hence, technology was flowing into the university from industry with the labor movement of corporate lab scientists Akasaki and Pankove. This pattern would repeat again in the late-1990's when Nakamura moved to UCSB to join DenBaars and Mishra's research team.

Such a pattern is not uncommon among engineering faculty. Indeed, of the UC engineering-based inventions licensed and developed by inventor-founded start-ups a number of the inventors had worked previously in industry, including Nitres' founder DenBaars (Hewlett Packard). Agility Communications founder Larry Coldren, as mentioned above, and Bandwidth9 founder Connie Hsien-Chang both worked at Bell Labs in the early 1980's.

4.1.2 Research at UCSB

Around the time of Nakamura's GaN lab prototype, DenBaars and Mishra began talking about potential applications in lasers and microwave transistors-applications that other researchers had not focused on. As Mishra described:

> Akasaki and Nakamura were concentrating on a certain aspect, which of course is the commercially more important area: colored lighting. But then we decided to make some blue emitters, some lasers, and some microwave transistors… The first time we went to a conference, we went without a paper. We just went to listen. At the next conference, we had a substantial presence giving papers.

Both UCSB professors had been working on gallium-based materials for some time. DenBaars, a material scientist, developed expertise in growing and developing materials for use in LED's first at Hewlett-Packard's Optoelectronics research group (1988-1991) and later at the University (1991-present).

As DenBaars and Mishra began to work on GaN, established firms played crucial roles in funding research at the university. Hughes Electronics had long (()/())maintained relationships with Mishra and UC-Santa Barbara's engineering school, contributing financial gifts, but no formal research grants, to the university. These gifts came without expectation of licenses and exclusive rights to research results, but were mechanisms by which Hughes researchers and management could access and develop long-term relationships with UCSB researchers, outside of formal patenting and licensing arrangements. These relationships also allowed Hughes to access promising graduate students and for lab managers to stop by and discuss research with Mishra with "no talk of (intellectual property) rights, ever."

When Mishra and DenBaars set out to start a laboratory at UCSB for the study of GaN and related research, it was these gift contributions by Hughes that helped seed the lab, with no formal contractual arrangement, as well as a grant from the U.S. government. Additional funds for the lab came from a Japanese LED manufacturer, who eventually took options- but no licenses- on inventions coming out of the UCSB lab.

4.1.3 Founding Nitres

DenBaars and Mishra recognized that their research had significant potential for multiple commercial applications. Mishra mentioned their decision to found a firm to his contacts at Hughes, and a Hughes manager suggested bringing in former Rockwell executive Fred Blum to run the business side, leaving DenBaars, Mishra and a handful of graduate students to continue developing the technology. DenBaars, Mishra and Blum founded Widegap Technologies (aka WiTech) next to the Santa Barbara campus in 1996.

For initial funding, the firm turned to established firms and government grants. Hughes Electronics and later General Electric offered matching funds for a Small Business Innovation Research (SBIR) grant and a National Institute of Standards and Technology's Advanced

Technology Program (ATP) grant, respectively. Research during the first few years was funded primarily through a series of government grants, often cosponsored with the university or these established firms. Eventually, projects for military applications were also funded by the Defense Advanced Research and Projects Agency (DARPA) and the U.S. Army.

An interesting aspect of Nitres' funding history is the lack of involvement of venture capital, equity markets, and the like, despite the backing of major research companies. Nitres, like many university-based start-ups, was pursuing very early stage and uncertain technologies on minimal budgets. Blum attributes Nitres' funding history to the early stages of their technology,

> We didn't even approach any VC's initially. We raised angel funding, but that was through my professional relationships with industry executives in the Los Angeles area. We didn't want VC money initially because they want to see a prototype too soon, and the technology was still too fragile. If they don't see a product coming up soon in the process, VC s get worried and can put unreasonable pressure on the company.

As a result, early finances were tight. No wages were paid for the first several months, and the firm limited investment in obtaining intellectual property rights until research was farther along.

The university did play an important role early on in providing a laboratory environment for Nitres in which to conduct research. Until the purchase by Cree, Nitres maintained Spartan offices only a few miles from campus and conducted a portion of its research in a clean room at UCSB, charged at an hourly rate. At least some of the investments necessary to start a semiconductor firm could be delayed during the early years by contracting with the university for use of research facilities, thus reducing a substantial barrier to entry.

4.1.4 Intellectual Property

"We were filing patents at the university, pretty aggressively at first.... We were filing patents, and the university was marketing those patents, but our past experience has been with university patents that large companies generally are not interested in licensing. They're interesting in doing it themselves" DenBaars 2000). One of Nitres' founders illustrated the challenges in marketing university inventions and their intellectual property: in some cases, established firms prefer to research and develop technologies entirely in-house.

As noted above, GaN was a much sought-after technology. Even today ongoing research at Siemens, Hewlett-Packard, Matsushita, Toshiba, LumiLEDS (a joint venture between Agilent Technologies and Phillips), and other large firms is targeted at developing gallium-based technologies for applications in their own products and to supply other markets. Several established firms reviewed Mishra's inventions through secrecy agreements. Yet only one firm, Cree, actively sought out the GaN technology developed by Mishra and DenBaars at UCSB. Although Cree never completed a licensing agreement for the technology, Cree accessed the technology by acquiring Nitres. In fact, Nitres also did not take a license. The inventors did sign letters-of-intent, but these short-term agreements expired as Nitres continued to develop the technology.

Part of the difficulty in marketing these patents was that most of the early UC patents were for processes that were small-scale in relation to that needed for commercial production batches. Indeed, one of the early challenges for the Nitres research team was to develop different crystal growth and production processes to accommodate (eventual) large-scale manufacturing.

Another important aspect of technology transfer that is not formally captured in university licensing arrangements concerns the importance of personal know-how and experience with the technology. Indeed, as DenBaars explained:

> Especially in the semiconductor business… the basic way big companies get at your technology, is to get the know-how, and that's done by hiring your students. Then [the technology] is in the public domain. The most important thing, at least in the semiconductor field, is know-how: knowing how to do something, and all of the amassed knowledge during the course of your Ph.D. So, the students are the most important resource we have. I'd say they're much more valuable than the patents.

4.1.5 Summary

By 2002, several companies including Cree market GaN blue LED's. Sales growth has been slow, though legal disputes between Nichia Chemical, Cree, and Nakamura have kept the key players in the spotlight. DenBaars and Mishra continue research at UCSB, and Nakamura joined the UCSB as a full-time faculty member. Pankove runs a small research company, Astralux, in Boulder, Colorado focused on wide-bandgap semiconductors. Founded in 1992, the company has been funded almost exclusively by government research grants. Akasaki is an Emeritus Professor at Nagoya University and Professor at Meijo University. Pankove, Akasaki, and Nakamura have received several prestigious engineering awards and public recognition for their work on LED's and wide-bandgap semiconductors.

The history of GaN and the rise of two start-ups in this field, Nitres and Cree, highlight several important issues related to the role of start-ups in developing university technologies further. Two are highlighted here. First, the technology had been researched for many years, and the full development of GaN was really the culmination of research at universities, small firms and start-ups, and established firms. The field grew from early research at corporate basic research labs, many of which no longer exist, and universities only became visibly involved decades after corporations pursued the technology.

Secondly, intellectual property plays an important role, evidenced by over 120 patents related to GaN granted by the U.S. Patent and Trademark Office (USPTO), but licensing rights to university patents did not appear to be the sole factor, or even a significant one, in the inventors' decisions to found a firm. As the Nitres founders suggest, access to the original research team, whose experience and know-how gained from working with the materials provide significant value, was the most important aspect of technology transfer.

4.2 Xenometrix

In many ways, Xenometrix represents the archetypal high technology start-up in the 1990s: a biotechnology firm built up from university research, with initial funding by venture capitalists and a public stock offering after a few years of development.

However, Xenometrix' experience also displays several similarities to Nitres, which in many regards was at odds with any standard depiction of high-tech start-ups. For example, at

Xenometrix the inventor's experience and personal knowledge were perceived as critical in developing the technology and in transferring the technology to customers. Also, the technology licensed from Berkeley, the Ames II Tests developed by Pauline Gee, were based on research that had been conducted two decades earlier, a fact that supports the notion that many start-ups are founded on technologies with a familiar scientific basis.

4.2.1 The Ames II Tests: New Research on Familiar Technology

The Ames II Test was based on assays that have been around for over 20 years. Bruce Ames developed the first version, the Ames Test, in the 1970's in his Berkeley lab. The original Ames Test determines the mutagenic potential (the ability to cause mutation) of a substance, such as a pharmaceutical, based on exposing the substance to a strain of Salmonella typhimurium bacteria. These bacteria strains have been chemically modified so that they can no longer manufacture an amino acid, histidine, necessary for growth. Once mixed with the substance of interest, some of the strains will mutate and grow just as a non-modified or "wild type" bacteria would. The test is then to count the frequency of growing colonies of bacteria-those that have mutated to be able to manufacture histimine.

The Ames Test is used on chemicals, pharmaceuticals, and foods to assess their mutagenic strength; the tests are also commonly used to test carcinogenic potency, which strongly correlates with a substance's mutagenic potency. The widespread availability of the bacteria strains have led to, by some estimates, over 10,000 different mutations created by scientists, of which five are used commercially on a regular basis.

After Ames disclosed his invention in 1975, he recognized the potential usefulness of his invention as a simple test for mutagenic and carcinogenic properties. Ames made the test available to academic institutions and industry. Seventeen years later, the Berkeley campus still maintains a small office to administer the Ames Tests, where any laboratory can receive samples for a small administrative fee. As a result, the Berkeley E. Salmonella Mutagenicity Test Resource Center, who until 2002 managed distribution of the Ames Test, estimated that the Ames Test is used in an over 3000 laboratories, including each of the major pharmaceutical companies[3].

As a post-doc in Bruce Ames's lab, Pauline Gee along with another researcher Dorothy Maron, set out to genetically engineer the bacteria strains to have specific mutations. In essence, Gee and Maron turned different genes on and off in each bacterium. The Ames II tests includes a set of six bacteria with every possible mutation (combination of genes turned on and off). These mutations allow for test data to be collected not only on whether the studied substance has mutagenic potency, as did the original Ames Test, but which of the six possible gene base substitutions occurred during a mutational event. Thus the Ames II Tests provide richer information regarding the specific mutation that occurs. These genetically engineered strains and the process to make them were patented by Gee, Maron, and Ames (US Patents 5681737 and 5869258) and assigned to UC-Berkeley. However, the original Ames Tests and other subsequent generations have never been patented.

4.2.2 Xenometrix' Background

In the summer of 1990, Pauline Gee had just returned to UC-Berkeley after spending time as a visiting scholar at Stanford University. Gee had previously been at Berkeley as a

[3] In 2002, Xenometrix assumed distribution duties for the original Ames Test.

research fellow in the Biochemistry Department and continued to supervise her Berkeley project on weekends and after hours while commuting to Palo Alto for her two years at Stanford.

At Berkeley, the scientist worked in the labs of Bruce Ames. During her weekend visits and first few months after returning full-time to the lab, Gee got to know Spencer Farr, a visiting scientist on his way to take a position as assistant professor in the School of Public Health at Harvard University. Gee and Farr were not working on exactly the same research, but had similar research interests in how bacteria respond to chemicals in their environment. The two scientists overlapped in Ames's labs full-time for only a few months in the Ames labs, but they would eventually become colleagues and later competitors.

Back at Harvard, Farr began working on human cells and bacteria, researching how responses to various chemical agents could indicate toxicity in the agent. By 1991, Farr realized that his research offered a cheaper alternative to the expensive process of animal testing at pharmaceutical labs and cosmetics companies, using human liver and colon cells and E. coli bacteria. As his results were made known, venture capitalists from the Castle Group, a VC firm specializing in medical technologies, initiated the process of forming Xenometrix when they contacted Harvard to conduct an assessment of the potential market for Farr's work (Cromie 1996). The market looked promising, and Xenometrix was founded in 1992, initially under the name Venmark, by two investors, Lindsay Rosenwald and John Prendergast, and the young Harvard professor, Spencer Farr, to further develop the technology. Prendergast was the managing director of Castle at the time. Rosenwald, a medical doctor by training, had founded Interneuron Pharmaceuticals in 1989 and would eventually found a venture capital firm, Paramount Capital, in 1993.

Although the company was originally founded on Farr's invention, Gee's work at UC soon became part of the firm's technology base. Shortly after the founding, the company reincorporated under the name Xenometrix, moved to Boulder, Colorado, and exclusively licensed the genetically-engineered bacteria assays invented by Gee and Maron. Along with the exclusive license from UC- Berkeley, Farr brought in lead inventor Pauline Gee. As Gee recalled, "Spencer knew that I had been working on the strains. He knew when he was forming the company that he really wanted the technology. The way of getting it was to hire me." Gee began as the Chief Science Officer, working to develop both her invention and Farr's invention, Gene Profile Assays.

As Xenometrix progressed, Farr decided that it was time to move on. In 1995, Farr moved to Sante Fe, New Mexico to found Phase-1 Molecular Toxicology. Farr's mission at Phase-1 was similar to Xemonetrix': to build up a suite of biotechnology products for measuring toxicity levels. Phase-1 licensed back Farr's invention directly from Xenometrix, since the Boulder firm jointly holds the patents on Farr's research with Harvard. Interestingly, this license leaves a complicated money trail, whereby Phase-1 pays royalties on sales of Farr's invention back to Xenometrix, who in turn pays a share of those royalties to Harvard. Harvard then provides a share of this payment back to Farr at Phase-1 as the original inventor. While the two companies continue to compete on Farr's invention, the Ames II Test was never licensed by Phase-1.

A striking aspect of the Ames II Test is that these assays are based on research that had been under way for 20 years and was used widely by industry and academic institutions. The Gee et al. research team's contribution was to apply the relatively new science of genetic engineering to create strains that would provide richer information on proven technologies. The challenge, then, was to ensure that Xenometrix technology could not be easily appropriated, particularly since so many laboratories had used the Ames Test for many years.

4.2.3 Intellectual Property and Inventor Know-how

The Ames II Test illustrates the importance of inventor know-how in working with the technology. As mentioned above, the initial transfer of technology from UC to Xenometrix was more than a simple licensing arrangement. Although faculty often consult with licensees to enable the technology transfer process, rarely do these firms hire the faculty. Rather, the lead inventor was hired in as the company was being founded. Two further pieces of evidence further indicate the importance of inventor know-how.

Inventor know-how is contracted upon in many of the agreements signed by Gee. For customers, typical contracts with Xenometrix include a provision whereby Gee will consult with the customer to transfer her know-how over a specified period of time. These contracts are similar to those discussed by Arora (1996) which allow firms to manage tacit knowledge related to an invention by specifying the consulting obligations of the inventor.

Another piece of evidence suggesting the importance of inventor know-how in the Ames II Tests is the difficulty Xenometrix' own European distributor, who was sublicensing the technology, had in replicating the bacteria strains. Ph.D. scientists at the distributor, Xenometrix GmBH, had independently attempted, based on a written set of procedures and quality control standards, to develop their own supply of the bacteria strains to ensure a constant supply should Xenometrix cease to exist. After a year of effort, including a week of training on the manufacturing equipment in the Xenometrix labs, the distributor scientists were still unable to produce a supply of strains that met the company's specifications and could be sold to customers. As a result, Gee traveled to the distributor's European labs to work with the scientists, manufacturing two years' worth of supply in a matter of days. Gee described:

> All of the manufacturing procedures were written in extreme detail. We have standard operating procedures for the manufacture… We do everything in [standardized processes] because we had a director of manufacturing that came out of the nuclear radioisotope field who was trained in ISO 9000. We specified how to calibrate the instruments with a separately independent force. Given all of that detail, they still were not able to manufacture it.

Both of these points suggest the significance of inventor-specific knowledge that is difficult to transfer through written specifications. The above examples do not conclusively prove the presence of tacit knowledge. That is, these examples do not disprove other counterfactuals, such as that the scientists at the distributor were underqualified to perform such work or Xenometrix was withholding critical procedures that could have be written down. On the other hand, one certainly cannot discount the importance of tacit knowledge, and these points are highly suggestive that Gee's tacit knowledge was an important component to transferring the Ames II technology.

Moreover, this case does not suggest that patents aren't perceived as important to the company. Gee still recognizes the role of patents as protection:

> Companies have wisened up to the fact that the value is not just the patent… My experience is intangible, whereas IP is tangible, and we can wrap legal language

around the IP in our agreements. Clearly what you want is both, but the IP's protection is necessary in case someone tries to steal our technology.

4.2.4 Summary

This brief history of the Ames II Test and Xenometrix demonstrates the important role of an inventor in further developing his or her technology. Gee was brought into the company early on as the lead inventor, and her employment was vital to ensuring the commercial development of the Ames II strains. To be sure, an established firm – particularly one of Xenometrix' pharmaceutical customers – could have licensed the Ames II Test and hired Gee, although this would be a costly investment for one firm to make for a new, unproven version of an established technology. This case study provides an additional piece of the puzzle to studying university-based start-ups, but does not fully provide a complete understanding the role and incentives of inventors in founding firms.

One interesting aspect of the Xenometrix case is that Gee was hired as part of the technology transfer process (from university to firm), rather than as a consultant. Again, no hard and fast conclusions can be made about this point, but it raises an interesting issue about contracting for personal (knowledge) assets: bringing the owner of the knowledge asset in-house can be a preferred mode of organization to simply writing a detailed contract. To the extent that entrepreneurship, under some definitions and uses, is primarily concerned with the process of and reasons for founding new firms, closer attention to the extensive literature on contracting and organization theory will shed light on entrepreneurship research questions.

4.3 Pangenix

Pangenix is a biotechnology firm that sells and licenses its Pantropic Retroviral Expression System, developed by the company's founders at the UC-San Diego (UCSD) School of Medicine. Pangenix' technology consists of retroviral vectors, agents that transfer material from one cell to another. Such agents are adaptations of a virus, but cannot replicate themselves. They can only be replicated by researchers in the laboratory. These vectors can be used to introduce foreign substances into a cell, producing a transgenic organism. Thus, the vectors can be used in a wide variety of cells (pantropic).

Pangenix was founded by a team of UCSD researchers, led by Dr. Jane Burns who is the company's CEO. In their UCSD lab, the researchers used the vectors for two applications, human gene therapy and transgenic therapies for animal and non-mammalian cells. Pangenix focuses on the latter application, with the first applications targeted to protect commercial stocks of oysters, clams, mussels, and abalone from disease; improve growth rates among striped bass; and introduce additional proteins into cow's milk.

The Pangenix case is noteworthy for two reasons. First, a number of companies, including several start-ups, were interested in utilizing the technology, even after it was in a developed form. However, to access the technology, the interested firms developed relationships and signed formal contracts with the inventors' firm rather than pursue simple licenses with the University. Second, on a related point, Burns articulates how inventor knowledge is transferred and how the role of tacit knowledge manifests in licensing transactions. Similar to Xenometrix, Pangenix' success relies on the inventors' abilities to work closely with customers and users of their technology. While there was considerable commercial interest in using the technology, the value lies in Burns' own experience and personal know-how in working with the vectors.

4.3.1 Initial Research: From Kawasaki to Oysters

Although Pangenix' first applications were for fish and sealife, Dr. Burns is not an ichthyologist. To the contrary, Burns spent much of her research career studying Kawasaki Disease, first at the University of Colorado and later at Harvard Medical School. Kawasaki Disease is an acute systemic illness that almost exclusively affects young children and can lead to childhood heart disease. Kawasaki Disease has remained elusive to scientists for decades: by 2002, there is still little know about the cause and early detection of Kawasaki Disease.

In the late-1980's, Burns was on staff at Boston Children's Hospital and, along with her husband, at Harvard Medical School. However, a career opportunity for her husband brought her and her family to San Diego. At the time, Burns was in the final stages of an NIH grant to study whether Kawasaki Disease was caused by a retrovirus[4]. Without a permanent appointment at a university in California, Burns looked for research lab positions. In this process, Burns met Ted Friedman, a professor of pediatrics who was leading a UCSD project on human gene therapy. A research position was opening as a Japanese post-doc on the team was leaving the university, and Burns joined the project in late 1989.

The project was to develop and apply a coat to retroviral vectors that would strengthen the usually-fragile vectors and allow for the vectors to be injected with better success. Once the vectors were strengthened with a protective coating, it was believed that vectors could be injected into foreign hosts – that is, cells that the base virus cannot not usually enter. This application would allow for gene therapy, micro-injections, and other uses. The original project team was already having some success developing a coating that was suitable for human gene therapy, and disclosed their initial findings to the technology transfer office at the time Burns joined the team. Within a few months, the university filed for a patent on the invention.

Burns worked principally with Friedman, and two other researchers in the Pediatrics Department at UCSD, Jiing-Kuan Yee and Atsushi Miyanohara. The research was funded by both the NIH and a major San Diego biotechnology company, Viagene, and proved to be successful within just a few years. By 1993, Burns, Friedman, and Yee disclosed to the university a vector that could be injected into non-mammalian species. At the same time, the San Diego scientists published their results in the Proceedings of the National Academy of Sciences (PNAS), the first of more than a score of papers by Burns and various collaborators related to pantropic retroviral vectors. As Burns recalls, "After our original PNAS paper in 1993, people read it and [companies] started to get in touch with me. We were looking for collaboration and welcomed the chance to talk to [them]" (Burns 2001).

4.3.2 Commercial Interest

A number of companies initially expressed interest in licensing the vectors for a wide variety of uses. Six companies, including Viagene and a few start-ups, reviewed the inventions at the university. Applications ranged from dyeing pet fish to genetically modifying animal embryos. However, no licenses were initially executed.

Rather, one interested company, Gala Design, approached the San Diego research team about collaborating. Several researchers at the University of Wisconsin were starting Gala

[4] A retrovirus is a class of viruses that contain RNA and reverse transcriptase. Retroviruses cause some types of cancer as well as AIDS.

Design to express proteins for use in pharmaceutical discovery. The Wisconsin researchers specifically sought to increase the level of protein in cow milk by using retroviral vectors to carry genes into a cow's mammary glands. Gala Design's interest provided a vision for the San Diego inventors to recognize commercial applications for the vectors.

The San Diego team decided to found a firm to supply vectors to Gala Design. Pangenix was founded with $1500 investments by Burns, Yee, and Miyanohara, plus $500 from Friedman, and a limited license from the university. The license was a "field-of-use" license limiting Pangenix' use of the technology to non-human applications, leaving the opportunity for another firm to license the technology for human gene therapy.

4.3.3 Inventor Knowledge

When Pangenix was founded, the technology was already close to a developed format for commercial sale, and the company only needed to hire and train an additional employee to produce the vectors. The company soon generated sales to a Singapore exporter of pet fish and a sub-licensing agreement with Gala. However, shipping biological materials across state lines requires expensive administrative work, and the company could only feasibly sublicense the technology in the U.S. for production at the licensee's labs.

After its founding, a number of companies approached Pangenix, including pharmaceutical firms, biotechnology firms, and hybrid fish and chicken farms. Burns recognized that the considerable commercial interest suggests that UC should have had no problems licensing the technology. Stated differently, given considerable interest by a number of companies, why a start-up? In an interview, Burns explained that the start-up was a vehicle to ensure access to the inventors' knowledge:

> The obvious question is 'Why didn't UC license it directly?' Of course, Pangenix wouldn't exist. But, what do the companies get when they license from UC? When they license from [Pangenix], companies are guaranteed access to my experience... If the university was licensing it around, we would be getting phone calls from people constantly asking about problems. I wouldn't be as sympathetic... Academic researchers can call me anytime, but that's because I'm part of this collegial profession.

As evidence, Burns reported that she receives calls regularly from customers trying to solve various lab problems in implementing the vectors:

> Customers call me and say “we were having problems working with this” and usually I can respond based on my experience: “we were working on that problem not too long ago and found these solutions”... I don't differentiate between knowledge gained conducting research in my lab and while working on Pangenix projects. Its in my head and I can transfer it to people when they use our vectors.

4.3.4 Summary

Burns' statement reveals that implementation of Pangenix' vectors required considerable on-going discussion between the licensee and the inventor, and that doing so through a series of individual consulting contracts did not appear feasible. The start-up firm then functioned as a vehicle to facilitate knowledge transfer, where sublicenses are required to provide a meaningful contractual tie between the inventor and another firm. Knowledge flow was facilitated by the contractual relationships between buyer and seller.

However, knowledge flows through labor movement, as well. After Pangenix was founded, Viagene was acquired by Chiron. The combined firm hired Yee, the principal investigator on Viagene's funding for the research, away from the University and simultaneously negotiated a license to the vectors for use in human gene therapy. Thus, the firm secured inventor knowledge by simply hiring the inventor away from academia.

Finally, Pangenix' technology is a basic tool that carries a wide range of applications. Recall that interested firms sought to use the technology for a number of different applications. An interesting article by Scott Shane (2000) illustrates how such university inventions can be commercialized for a variety of uses based on the licensee's background. Taken together, one might argue that basic tools should be offered only as a non-exclusive license for different parties to utilize. Indeed, several critics of the Bayh-Dole Act have stated this exact proposition.

However, the Pangenix case illustrates how the inventor start-up may be a necessary vehicle to facilitate knowledge sharing between inventor and multiple licensees. To the extent that the inventor needs to engage in considerable post-license knowledge transfer with multiple parties, inventors may require stronger IP rights, such as those afforded by an exclusive license or a broadly-defined field-of-use license, to start a firm. Stronger IP rights are necessary for inventor start-up firms to establish a tradeable asset (via a sublicense, for example), assure a legal defense as Gee intimated in the Xenometrix case, and satisfy private and public funding organizations who provide capital.

4.4 Calimetrics

Calimetrics is an optical storage company that has developed a proprietary platform for high-capacity disk storage based on a technology called "pit depth modulation," or Multilevel Recording (the trade name). This technology allows for increased storage capacity for CD's and DVD's by recording data using different levels of reflectivity (or different depths of pits) on a disk. Recording at different levels also allows for faster data transfer to the disk media during a given time frame, effectively decreasing the time it takes to copy information onto a CD. The company's products include a set of related innovations: chipsets for audio and video players, CD and DVD media (disks), and a mastering system to record onto the media.

Based 9 miles from UC-Berkeley, Calimetrics was founded by two Berkeley graduate students, Terry Wong and Michael O'Neill, and a McKinsey consultant, Thomas Burke. The firm also operates a second research facility in Bedford, Massachusetts. The Bedford research team and facility were acquired from former research partner Polaroid Corporation when the film and photography company negotiated to withdraw from a research alliance including Calimetrics, Polaroid, Energy Conversion Devices and two universities, as discussed below.

4.4.1 Initial Research

The technology behind Calimetrics was developed from research conducted Wong and O'Neill at UC-Berkeley in the late 1980's. The two graduate students worked on measurement technology in the late Professor Alan Bearden's biophysics laboratory. Wong was developing an application for an imaging device, namely a specialized microscope, to map the profile heights of biological cells. O'Neill worked on related technology to study hearing, particularly the motion of inner ear components.

As their research progressed, Bearden and O'Neill disclosed their invention to the University and filed for patent in 1989. Wong and O'Neill graduated but continued to work as post-docs in Bearden's lab. When an electronics company that supplied their labs with equipment expressed an interest in licensing the technology, Wong and O'Neill introduced the firm to the Berkeley campus technology licensing office. The firm was interested in developing the research for imaging applications in the semiconductor industry to complement other products the company already produced, although the inventions was in a "raw" form and required considerable development effort. In 1992, the electronics company licensed the technology, and worked to develop the technology for several months. However, the licensee but soon ended its licensing agreement before fully developing the invention. The pit depth modulation technology remained an open case at OTT with no other companies interested in licensing.

The technology also could have been licensed by any one of several Japanese manufacturers of CDs or measuring equipment. Despite marketing efforts by the University, these firms were unwilling to take licenses on an unproven technology. Wong explained:

> Our experience is that the large Japanese firms, at least in this field, would not have licensed the technology straight from the university… [these] firms tend to look at evolutionary improvements in the technology, and this technology was totally different… another problem was that this technology was an idea in a patent and a couple of researchers. We spent 5½ years [at Calimetrics] getting to the point where we could even bring in Japanese companies, and they can see the technology… Only then can they begin to accept that this could be a commercial product.

By 1994, Bearden had retired from academia and considered other pursuits. The emeritus professor joined with an entrepreneur to found Quadrant Imaging to develop a working prototype of the microscope technology. The Quadrant partners' goals were close to the original research application, to develop a 3-D microscope for a variety of uses at an estimated one-tenth of the cost of similar microscopes on the market (Sanders 1995). After two years of further development, however, the death of Bearden and Quadrant's inability to attract private investment ended the fledgling firm's efforts.

During this time, O'Neill and Wong founded Calimetrics. However, the O'Neill and Wong set out to adapt the microscope technology for a different application than originally intended, to increase the storage capacity of compact disks. Their motivation for founding a firm seems to have been present long before discovering a potentially viable technology: "We knew from the start that we did not want to stay in the academy. Then this technology appeared to have some promise, and we saw it as an opportunity" (Wong 2000). The two researchers contacted Tom Burke, a college buddy, from their undergraduate days at Yale who had been working in management consulting to be the third founder of Calimetrics. The firm was founded with offices/labs in O'Neill's Richmond, California garage in 1994.

4.4.2 Funding Challenges

When Calimetrics was founded, its technology was rough and uncertain, limited primarily to lab test results, and no working prototype existed. There was a great deal of uncertainty over whether the technology would actually work at a commercial level. As a result of this uncertainty, both Calimetrics and Quadrant Imaging struggled to attract venture capital until a prototype could be produced. Although Calimetrics did have some private financing early on, the firm relied heavily on industry funding and joint initiatives to initially finance research and development. During the early years, Calimetrics brought in barely enough funds to maintain research operations, and even closed for a month in April 1997 between funding rounds.

As depicted in Figure 3, Calimetrics received its initial funding from a $1.8 million research grant from the Advanced Technology Program. Additional funding was provided by angel investors (including the CEO of the initial firm that took a license, among others), and a State of California program through what is now the California Technology, Trade, and Commerce Agency. In late 1997, Calimetrics received a second ATP grant jointly with Polaroid and Energy Conversion Devices (ECD). This $11 million grant was to develop a working prototype of the high-capacity storage technology for recordable DVDs. Matching funds of $10.3 million were provided by Polaroid and ECD. This project, Multiple Optical Recording Enhancements or MORE, is an ongoing collaborative led by Calimetrics and initially included the participation of both private firms (Polaroid and Energy Conversion Devices) and public universities (the University of Arizona and Georgia Tech). Polaroid eventually left the MORE project as the company began to scale back research in this field.

Shortly after receiving the NIST grant with Polaroid and ECD, Calimetrics received several million dollars from storage company Iomega to continue research. In exchange, Iomega received exclusive distribution rights to some of Calimetrics' technology. This deal posed another potential challenge for Calimetrics: developing a new standard in a technology area characterized by considerable network externalities. Part of the solution would be to ensure that the Calimetrics players and media were compatible with existing technologies. Moreover, the Iomega funding came at a time when Calimetrics was only beginning to gain acceptance from established firms.

As established firms began to invest in Calimetrics, the founders were finally able to access the venture capital market in late 1997, three years after founding the firm. Soon after, other major companies began to work with Calimetrics. Texas Instruments negotiated a license on the technology to jointly design and fabricate integrated circuits and resell them to Calimetrics.

As the first demonstration products were developed, Calimetrics was finally able to turn to the large, established Japanese companies in the disk storage industry, many of whom had been uninterested in the technology a few years earlier. In late 2000, TDK, Mitsubishi Chemical and Plextor created an alliance to bring Calimetrics technology to the mass market and create new technological standards for CDs. Sanyo joined the alliance two months later. In April 2001, representatives from over 60 companies on their way to the Optical Data Storage 2001 conference in New Mexico stopped off in California and paid to listen to Calimetrics' founders and development team discuss the current state of the firm's technology at a small conference center two miles from the company's Alameda headquarters.

4.4.3 University Relationships

Universities played a significant role as a source of research for Calimetrics. After the initial licenses, Calimetrics provided grants to researchers at UC-Berkeley. The firm also initiated talks to fund a Stanford graduate student's research to access research needed to move the company's technology forward, though the agreement was never completed. Although these research projects did not produce technology for Calimetrics, they do demonstrate the use of universities as sources of research for the company. Beyond these relationships, the

University of California has not been substantially involved in the further development of Calimetrics' core technology.

The company continued working with faculty from the University of Arizona and Georgia Tech, although Calimetrics has not licensed any intellectual property from either university. The ATP grant provides some funding for the University of Arizona's Center for Optical Data Storage, which was established in the mid-1980's to facilitate joint industry-university research. As part of this project, Calimetrics has commissioned several focused research projects. Burke explained:

> Maybe in years 2 or 3 for the company, as we were coming out of the first funding, we turned to Berkeley.… But, we haven't found anybody… in our industry at Berkeley.… When you're first starting out, you're dependent on the local roots of the company, but once we got the technology to a certain level, our aspirations for suppliers became global, and we scoured the world for individuals with world-class expertise in this industry. We found them at the University of Arizona and Georgia Tech.

The company also has relied on the involvement of a leading researcher in optical data storage, Georgia Tech Professor Steven McLaughlin. Calimetrics is the second start-up McLaughlin has helped to develop high-capacity storage disks. McLaughlin originally worked with a start-up firm in Rockville, Maryland, Optex Communications, that owned or licensed over 40 patents in optical data storage. McLaughlin was granted 16 of the patents assigned to Optex on data encoding methods; his research was funded by a $1.4 million ATP grant to Optex to develop a high-capacity CD storage technology using a form of multilevel recording and glass, rather than plastic, CDs. However, Optex faced two serious challenges to reaching commercialization: the lack of a low-cost, commercially-available green laser necessary to the technology, and no partners to help bring the technology to market. As a result, the firm's private investors pulled financial resources, and the firm declared Chapter 7 bankruptcy in early 1998.

McLaughlin first worked with Calimetrics as an consultant to the MORE project. He also assisted Calimetrics obtain rights to Optex' patents. McLaughlin later took a long-term leave of absence from Georgia Tech to become a full-time research scientist at Calimetrics in January 2001.

4.4.4 Summary

Calimetrics' experience recounts some of the themes of Nitres' history. Like Nitres, Calimetrics was founded on very early stage technology, and a prototype was years from development. Unable to access venture capital markets during the first three years, the firm relied primarily on state and federal government grants targeted towards early-stage research. As research and development progressed, the involvement of established firms through funding and licensing arrangements allowed Calimetrics to continue progress. It was only several years after the founding, and with the involvement of established firms, that Calimetrics was able to access significant venture capital funds. Nonetheless, Calimetrics is only now on the verge of releasing a commercial product, a testament to the long development time and significant uncertainty related to technology upon which the firm was founded.

The established firms involved early, including Polaroid, Iomega, Texas Instruments, and others, were not the traditional market leaders in CD's and DVD's. These firms were a mix of suppliers (Texas Instruments) and firms with related technologies. The industry incumbents only became actively involved with Calimetrics after the start-up had progressed through several early development phases, including substantial changes in the direction of the technology along the way.

5 Conclusion

This chapter presented the experiences of several start-ups founded on University of California inventions. The themes discussed indicate a need for more attention to university based start-ups and their role and contributions in technological advancement and regional economic growth. An important point raised by several of the case studies is that the previous focus on biotechnology and pharmaceuticals has been well placed – these are the most prolific areas in terms of university patenting and licensing activity – but may be missing part of the story.

For policy, a fundamental challenge is to establish institutions that respect potential differences among scientific fields and industries. Inventors and start-ups in non-biomedical fields appear to face quite different challenges and experiences, particularly with respect to obtaining venture funding and the perceived importance of intellectual property. In some cases, the inventor's personal knowledge was perceived to be a critical portion of technology that could only be transferred through the inventor's active involvement with the firm.

For scholars studying entrepreneurship and the economics of science and innovation, this chapter underscores the diversity of university-industry interactions. When viewed through the context of a long research path, at least in several of the case studies, a delicate dance among corporate labs, university research, and start-up firms is illustrated. More research is needed to further explicate the specific incentives, relationships, and roles of each party involved in a long research process.

Finally, to the extent that policies on university research and entrepreneurship rely on several accepted assumptions and beliefs regarding the importance of intellectual property and the ease of VC funding, this chapter calls some of those beliefs into question. There is a valid concern that policies on university licensing and faculty endeavors with industry might be formed without the full set of facts in hand. This suggests that more data gathering and analysis is needed to finish painting the picture of university-industry relations before deciding which frame looks best.

Works Cited

Akasaki, I. 1997, “Address by Professor Isamu Akasaki: Nitride Semiconductors”. *Material Research Society Symposium Proceedings*, Vol. 482, p. xxvii.

Arora, A. 1995, “Licensing tacit knowledge: Intellectual property rights and the market for know-how”. *Economics of New Technology and Innovation* 4, 41-59.

Arora, A. 1996, “Contracting for tacit knowledge: The provision of technical services in technology licensing contracts”. *Journal of Development Economics* 50, 233-256.

Bhidé, A. V. 2000, *The Origin and Evolution of New Businesses*, Oxford University Press, New York.

Blum, F.: 2000, Personal interview.

Burke, T.: 2000, Personal interview.

Burns, J.: 2001, Personal interview.

Coldren, L.: 2001, Personal interview.

Colyvas, J., Crow, M., Gelijns, A., Mazzoleni, R., Nelson, R., Rosenberg, N. and Sampat, B. 2002, “How do university inventions get into practice?” *Management Science* 26.

Cromie, W. 1996, “Harvard licenses test system for toxic chemicals.” *The Harvard University Gazette*, online edition http://www.news.harvard.edu/gazette/1996/04.25/HarvardLicenses.html.

DenBaars, S. 2000, Personal interview.

Eisenberg, R. 1996, “Public research and private development: Patent and technology transfer in government-sponsored research”. *Virginia Law Review* 83, 1663—1727.

Gans, J. and Stern, S. 2000, “When does funding research by smaller firms bear fruit?: Evidence from the sbir program”, NBER Working Paper No. W7877 .

Gee, P. 2001, Personal interview.

Giesecke, S. 2000, “The contrasting roles of government in the development of biotechnology industry in the US and Germany”. *Research Policy* 29, 205-223.

Jensen, R. and Thursby, M. 2001, “Proofs and prototypes for sale: The licensing of university inventions”. *American Economic Review* 91, 240-259.

Kahaner, D. K. 1995, “Blue led’s: Breakthroughs and implications”. Asian Technology Information Program, http://www.atip.or.jp/public/atp.reports.95/atip95.59r.html

Lerner, J. 1999, The government as venture capitalist: The long-run e□ects of the SBIR Program”. *Journal of Business* 72, 285-318.

Mishra, U. 2001, Personal interview.

Mowery, D. C., Nelson, R. R., Sampat, B. N. and Ziedonis, A. A. 2001, “The growth of patenting and licensing by u.s. universities: An assessment of the e□ects of the Bayh-Dole Act of 1980”. *Research Policy* 20, 99-119.

Pankove, J.: 2001, Personal interview.

Pankove, J.: 2002, Personal interview.

Polanyi, M. 1958, *Personal Knowledge: Towards a Post-Critical Philosophy*, University of Chicago Press, Chicago.

Press, E. and Washburn, J. 2000, “The Kept University”. *Atlantic Monthly* 285+.

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

Rosenberg, N. 2000, “America’s university/industry interfaces: 1945-2000”. Stanford University Working Paper .

Sanders, R. 1995, From academics to entrepreneurs, *The Berkeleyan*.

Sandhu, A. 1998, “Interview: Akasaki Isamu”. *Oyo Buturi International* 67.

Shane, S. 2000, “Prior knowledge and the discovery of entrepreneurial opportunities”. *Organization Science* 11, 448-469.

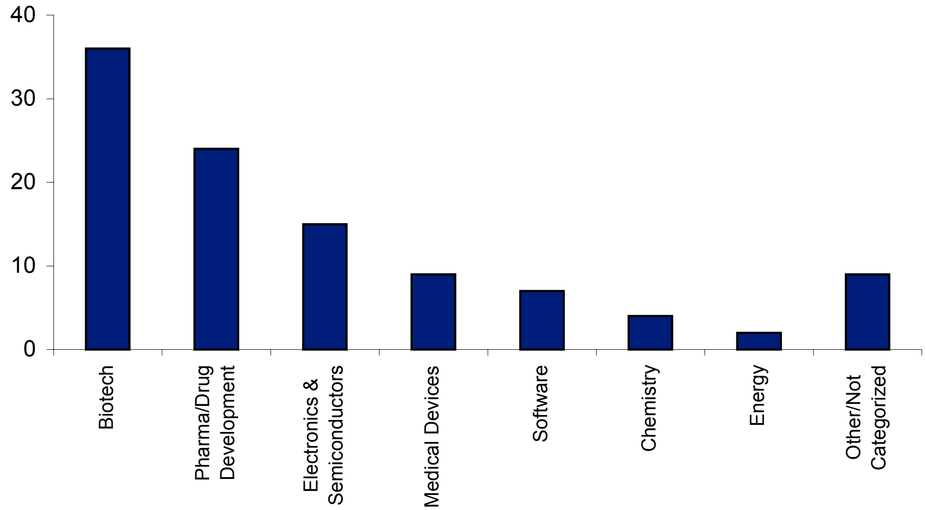
Wong, T. 2000, Personal interview.

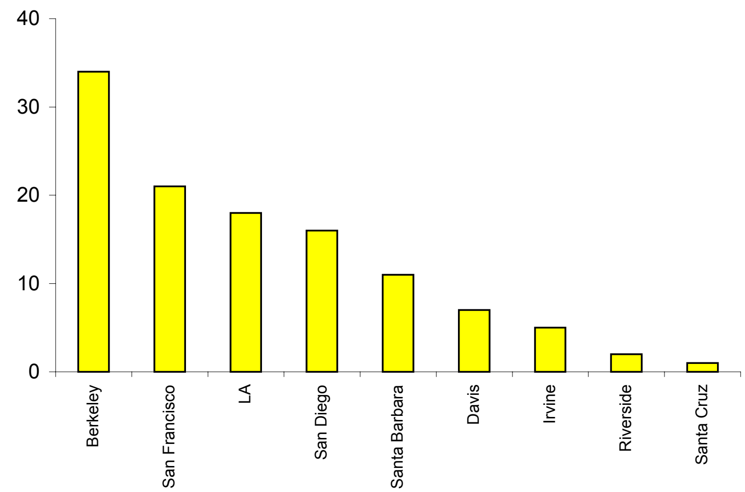
Zacks, R. 2000, The TR university research scorecard”. *Technology Review* 103, 88-90.

Zorpette, G. 2000, “Blue chip”. *Scientific American* 283, 30+.

Figure 1. Count of UC start-ups by technology area (left panel) and campus of invention (right panel). "X" marks the technology class and campus for each case study company.

Count of

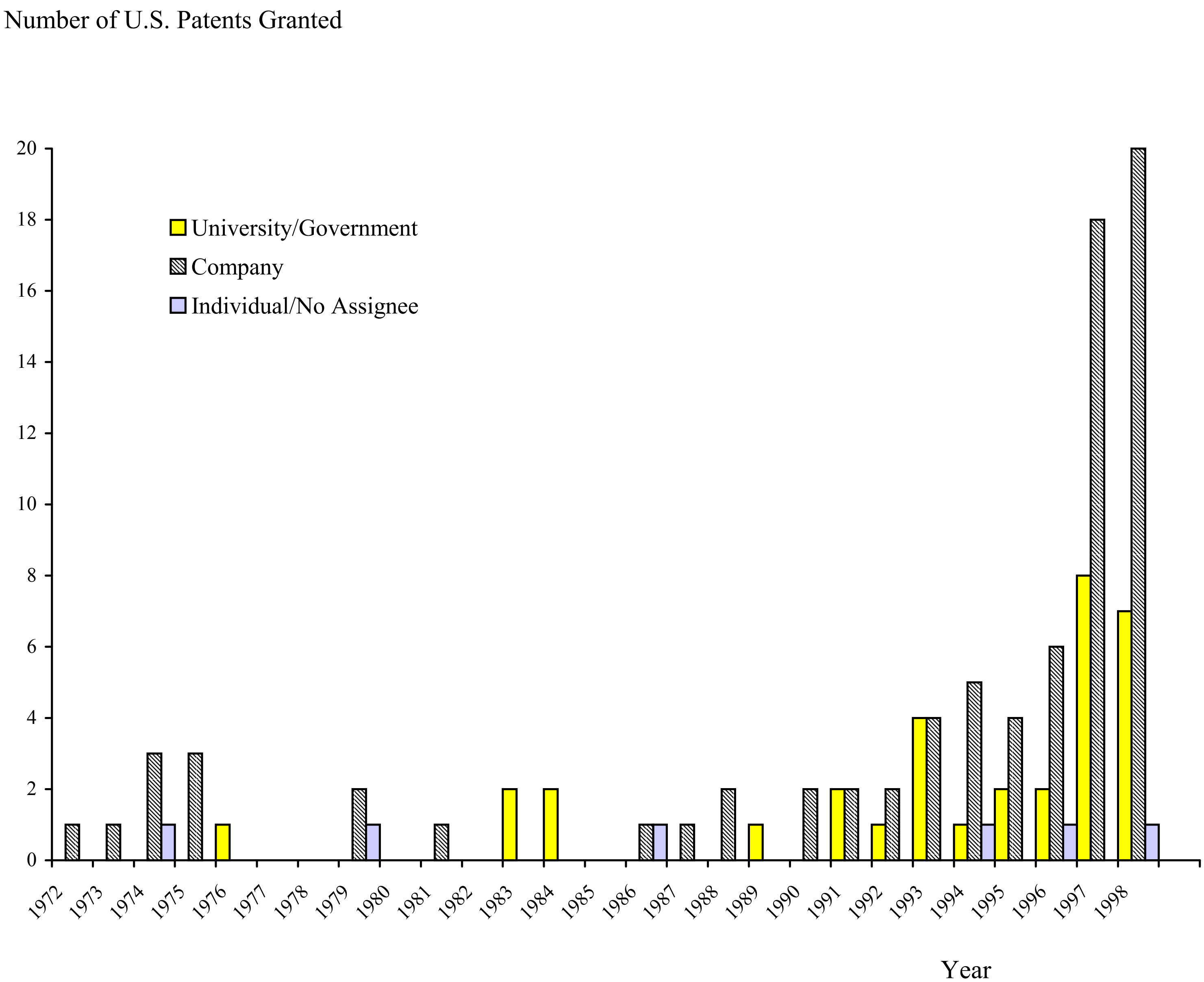




Firms

Firms	Biotech	Pharma/Drug Development	Electronics & Semiconductors	Medical Devices	Software	Chemistry	Energy	Other/Not Categorized	Berkeley	San Francisco	LA	San Diego	Santa Barbara	Davis	Irvine	Riverside	Santa Cruz
Agility			x										x				
Calimetrics			x						x								
Cortex		x													x		
Neomorphic	x				x				x								
Nitres			x										x				
PanCel		x										x					
Pangenix	x											x					
Xenometrix	x								x								
Company A			x						x								
Company B	x									x							
Company C		x								x							
Company D				x							x						

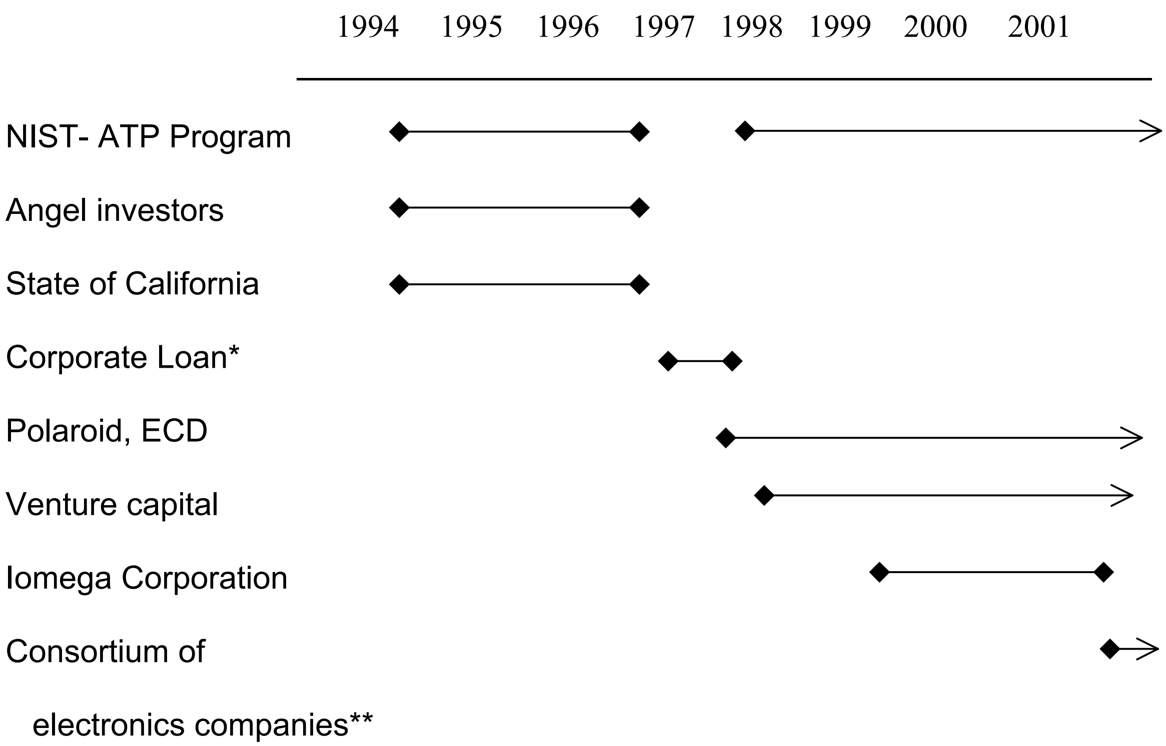
Figure 2: History of GaN Patents



Notes:

1) Patents related to GaN based on text search of patents with "gallium nitride" or "GaN" in either the title or abstract.
2) The 1976 patent was assigned to the "British Secretary of State for Defence"
3) Patents were coded as university-assigned if at least one of the inventors was at a university.

Figure 3. Calimetrics Funding Timeline



* Bridge loan from Creative Labs
** Includes TDK, Sanyo, Mitsubishi Chemical, Plextor, GATX Ventures