Inventing the Entrepreneurial University: Stanford and the Co-Evolution of Silicon Valley*
(アントレプレナーの地域：スタンフォード大学とシリコンバレーの共生と進化)

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Stanford is typically featured as a paradigm example among universities generating innovations that lead to new technology-based firms; and indeed, Stanford entrepreneurial activity is generally regarded as virtually synonymous with the birth of Silicon Valley. This is the stuff of legend, but it is based in fact: In a study conducted in 2000 Tom Byers and colleagues argued that Stanford alumni and faculty account for more than 1800 technology based firms in the Silicon Valley responsible for 37 percent of all high-tech employment in the region[1]; and in his contribution to the *Silicon Valley Edge*, Jim Gibbons, himself a Silicon Valley legend, argued that Stanford technology startups, including Hewlett-Packard, accounted for 60 percent of Silicon Valley revenues in 1988 and 1996 if Hewlett-Packard is included in the accounting and slightly over 50 percent if HP is left out of the mix.[2] But such accounts can be misleading. While it is undoubtedly correct that Stanford has been a significant factor in the formation of Silicon Valley, recognition of Stanford's role in Silicon Valley history should not be allowed to overshadow the enormous influence Silicon Valley has had in shaping Stanford itself. The relationship has been symmetric and co-evolutionary.

In our soon-to-be completed study Nate Rosenberg, Harry Rowen, Jeannette Colyvas, Brent Goldfarb, Christophe Lécuyer and I argue that while Stanford has indeed played an important role in shaping the industrial economy of the region, Silicon Valley firms and inventors have been just as important in shaping research directions at Stanford. The Silicon Valley, with its startups, large high-tech firms, venture capitalists, law firms, and academic and government research institutions is very much an ecosystem with crucial flows and interdependencies among its various sectors. Bill Miller has called it a habitat for innovation and entrepreneur-

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ship. The key to understanding these dynamic flows between the Valley and Stanford is the role of Federal support of research and development at major universities as well as the stimulus provided by federal R&D for industry in technology regions like the Silicon Valley. Stanford has contributed to multiple waves of innovation in Silicon Valley by successfully setting its sights on obtaining federal funding for scientific research that is at the same time industrially relevant. Creating and sustaining an entrepreneurial culture has been crucial to developing this synergistic feedback between federally supported research and research problems of industry, and it has positioned Stanford researchers to make major advances in science and engineering. This is the surprising outcome of our study: Stanford's entrepreneurial activity is actually an important source of new scientific directions that enhance the ability of its faculty to be competitive for research awards.

Stanford is fundamentally a research university with a commitment to graduate training. The primary, indeed almost exclusive source of its research budget is the federal government, particularly the NIH, the NSF, the Defense Departments and various other federal agencies. In addition to the federal government, during the past few years an increasing but relatively small amount of Stanford research (less than 5 percent) has been funded internally from its own endowment and from revenues derived from patents and licenses through the activities of the Office of Technology Licensing. But surprisingly (to me at least) very little direct support for research comes from industry. Thus, Stanford's ability literally to keep the doors open has depended on the success of its faculty in the award of federal grants and contracts.

Stanford has evolved a highly effective strategy for staying on the cutting edge of the research front. Stanford—and universities like it—has become a highly effective bi-directional node within a federally funded innovation cycle. On the one hand it has evolved as an entrepreneurial, highly flexible institution that actively seeks to absorb new technological and scientific breakthrough areas that spring up in industry in Silicon Valley and elsewhere and turn them into scientific research areas worthy of federal research support. Former Dean of Engineering, Jim Gibbons has called this "reverse technology transfer." Equally effective is the transfer of ideas, techniques, personnel and technology from federally funded research projects at Stanford into startup firms in the Silicon Valley area which occasionally pioneer path breaking new areas that transform the research landscape. But the contribution of institutions like Stanford to their regional economies is difficult to measure. Certainly training young scientists, engineers, legal and business minds for careers in industry is important, but it is impossible to measure the impact of such contributions. Also important is the invention and disclosure of devices, processes, and materials that are capable of contributing to industrial developments. Our study attempts to measure such factors. But if we press deeper into the features of university-generated innovations that have made a major difference and the institutional environment that has enabled those innovations to emerge, I would argue that a crucial element in the continuous synergism between Stanford and the Silicon Valley has been the presence at Stanford of an engineering school, a medical school, and an environment that encourages interdepartmental and cross-school collaborative work. Such collaborations have been fundamental in producing startup companies focusing on convergent technologies (such as computing and biotechnology, or nanotechnology and communications) that have been crucial to generating new waves of technological innovation. In what follows I will illustrate both processes: the process of reverse technological transfer and the production of path breaking discipline shaping research technologies that have emerged from the co-evolution of Stanford and the Silicon Valley.

The linkage of entrepreneurship and research at Stanford was born initially out of the historical circumstance of its (initially) less-than-advantageous West Coast location and circumstances connected with its small endowment as a private institution. During the intervening years Stanford's endowment has grown, placing it fifth among private institutions of higher learning. But even today at its height, Stanford's (2002) endowment is only 44 percent of Harvard's endowment, 85 percent of Princeton's, and 78 percent of Yale's.[3] Princeton's endowment per student, $701,146 ranks it the highest in the country. Stanford's $288,022 per student ranks in seventeenth position. The situation was much worse at the end of World War II when the administration of Wallace Sterling began to turn the situation around. In his 1997 state of the university address, President Gerhard Casper quipped that it was an intimidating task to lead an organization that has to raise roughly 88 percent of its budget each year. This is a situation every Stanford administration has faced, and it has contributed to the invention of a university that is aggressively entrepreneurial. Faced with a severe financial crisis following World War II Stanford administrators overcame their traditional aversion—shared by other private universities up to that time—to accepting federal funds and aggressively pursued new federal funding opportunities that became available after the war, particularly in areas related to military sponsored research, as well as in new federal and private foundation programs targeted at transforming American medicine.

Making Research Pay: The Centrality of the Research Mission at Stanford

Before we go further, I want to make clear just how important the notion of research—as opposed to applied science—and federal funding as an incubator of industrially relevant research are and have been to Stanford. As we shall see, the "recipe for distinction" developed by Frederick E. Terman and his colleagues in the Stanford administration in the 1950s was simple: focus on attracting and retaining the scientific and engineering talent most capable of winning federally funded research grants and contracts—steeples of excellence—and use those funds to support cutting-edge research that stimulates industrially relevant technology, which in turn reinforces the capability to do more and better research. That vision is as important today as it was 50 years ago. Since the late 1980s federal funding for research has been steadily declining in real terms for both federally funded programs at universities as well as funding of R&D in industry.[4] At the same time private funding of industrial R&D has increased significantly. For universities like Stanford, however, in spite of its entrepreneurial faculty and close ties to industry, industrial support of research has been relatively insignificant. The support of R&D at Stanford by different sources is illustrated in Figure 1 for the years 1995-2000. The chart makes it clear that Stanford raises approximately 90% of its research budget from federal sources. Figure 1 illustrates that in the year 2000, for example, non-government sources contributed $42 million in research funds to Stanford in comparison with $408 million in federal funds, excluding support for the Stanford Linear Accelerator Center (SLAC). Figure 2 illustrates the distribution of Stanford's total grants and contracts for the year 2000 in terms of the percentages received by the Schools of Medicine, Engineering and the Physical Sciences (included as a division within Humanities and Sciences). A striking feature of the funding detail illustrated here is the large percentage commanded by the Stanford Medical School, roughly 49% of the $408 million total, compared to 17% for the School of Engineering. Finally—and for us initially surprising—as Figure 3 illustrates, only 48% of the non-government funding Stanford received in 2000 derived from corporate sources. Thus, even in the banner years of industrial growth of R&D, a period in which corporate R&D accounts for more than 60% of total US R&D, and in which one might expect institutions such as Stanford would turn increasingly toward private funding sources, Stanford has depended almost exclusively on federal funding for support of its research mission.

Figure 1. COMPARISON OF U.S. GOVERNMENT AND OTHER CONTRACT AND GRANT EXPENDITURES

For the Years Ended August 31, 1996-2000

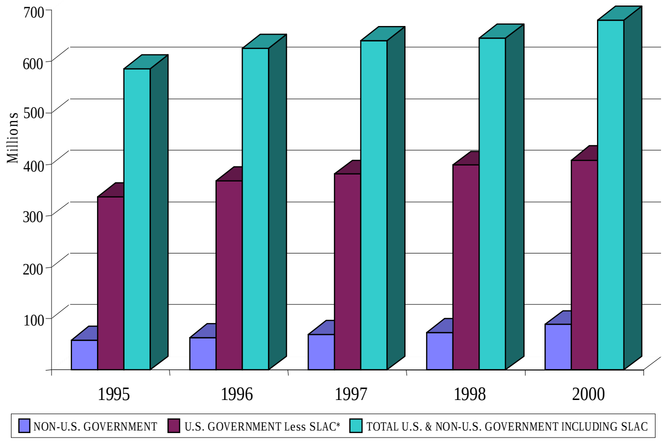


Figure 2. TOTAL STANFORD GRANTS AND CONTRACTS

FY 2000 in Millions of Dollars

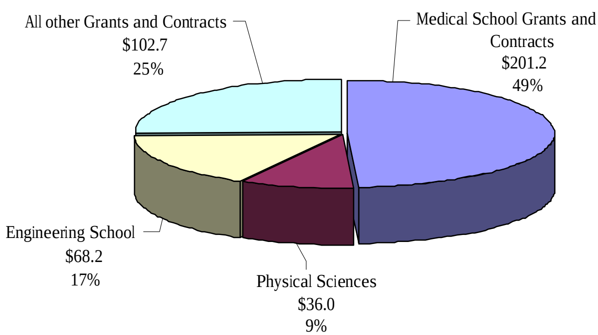
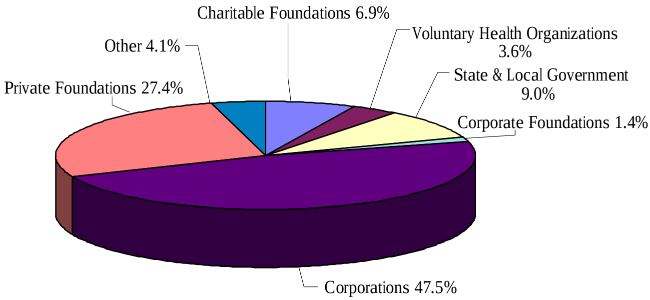


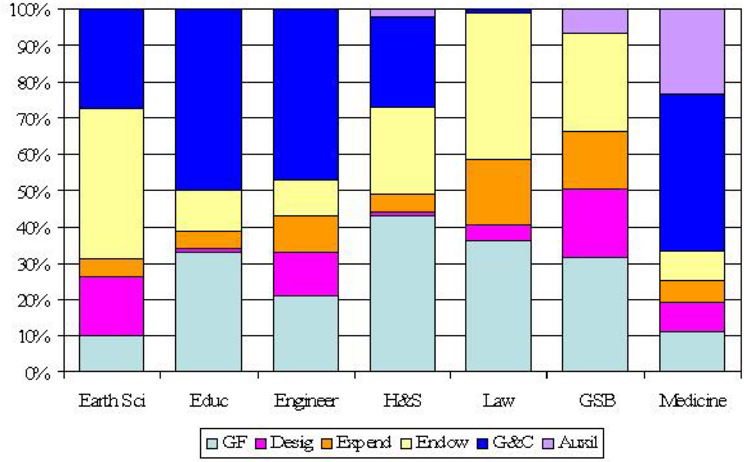
Figure 3. STANFORD UNIVERSITY NON-U.S. GOVERNMENT CONTRACT AND GRANT EXPENDITURES PERCENT OF CONTRIBUTION

For the Year Ended August 31, 2000



The 2002-03 fiscal year was a "lean" year for Stanford, a year in which it drew heavily on endowed funds. Sponsored research, consisting of grants and contracts from primarily federal sources, constituted 36%, or approximately $825 millions of the $2.3 billion total revenues of the university for 2002-03. This figure was more than twice that from the next largest sources of income: namely, income derived from the endowment (18%), and from student tuition and fees (15%). How this played out in the operations of the different academic units of the university underscores the significant, indeed defining, role of research at Stanford. For the year 2002-03 the School of Engineering covered approximately 48% of its combined teaching and research operations from its research grants and contracts. A similar financial picture emerges for the Stanford Medical School. Roughly 47% of the entire operating budget of the typical medical school department at Stanford is derived from grants and contracts. Today in centers like the newly opened Clark Center, the Photonics Research Center, the Stanford Nanotechnology Center, or in the Biomedical Devices Network patterns of entrepreneurship that draw upon federal funding to sustain the co-evolution of Silicon Valley with Stanford science and engineering are busy laying the foundations for the next wave of innovations.

Figure 4. 2002/03 CONSOLIDATED BUDGET FUNDING COMPARISON OF ACADEMIC UNITS



The Terman Model: Steeple Building and the Recipe for Distinction

The basic model for the research university that Stanford has become was developed by Frederick Emmons Terman during his years as Dean of Engineering in the years immediately following World War II. In 1945 Terman returned from his wartime position as director of the Radio Research Laboratory (RRL) at Harvard to take up new responsibilities as dean, and he came with a plan for putting Stanford's engineering school on the map as one of the premier programs in the nation. It was a plan born of his experience managing the RRL, combined with observations of the administrative structure and philosophies of Harvard and MIT. As a former student and close friend of Vannevar Bush, Terman was privy to the discussions in Bush's circle about building a post-war alliance among government, industry and academe, the vision Bush set forth in his 1945 Report to the President entitled, *Science the Endless Frontier*. While still at the RRL Terman began to shape a formula for success. It involved using government funding, principally ONR contracts, to build 1) a premier faculty in areas of electronics, which Terman was confident would be the major engineering growth area in the post-war environment; 2) build a large Ph.D. program, transforming the curriculum from one focused solely on practical engineering training to one infused with physics, mathematics and the social sciences. Terman and a handful of his close academic friends believed that the university would be the key to postwar industry. In the research triad—government, industry, university—Terman believed the postwar university was the source of key innovations. Terman brought three ONR contracts for work in microwave physics and engineering with him when he returned in 1945-46. These resources were the beginning of a new university.

The primary resources for Terman's vision for Stanford were government grants and contracts. In contrast to some of his colleagues at Stanford, such as Board of Trustee President, Donald Tressider and even the President of Stanford, Wallace Sterling, Terman hoped to build close alliances with industry, but he did not think industry funding held the key to building a university in the post-war era. A number of efforts had been made by universities such as MIT before the war to finance research with industry funding, all with mixed results. Stanford's experience with the klystron patent in the late 1930s was typical. The invention was made by physicist William Hansen and developed by Russell and Sigurd Varian. Licensing the patent to Sperry Gyroscope promised to supply the Hansen lab with ample funding to pursue their research in other microwave devices. But the relationship proved to be unsatisfactory.

Industrial sponsors of academic research like Sperry wanted control over the direction of research in the lab, and they wanted to insure exclusivity with respect to inventions coming out of the lab. Hansen, for example, found that Sperry would not give him, his colleagues, and students free reign to pursue their own research on klystrons and other microwave devices the group believed would ultimately benefit Sperry Gyroscope. Moreover, industrial sponsors only wanted to fund work directly related to their own interests. They were not necessarily interested in furthering the academic mission of the lab (or university) through funding of fellowship programs, building construction, or purchase of instruments and equipment not directly related to their own goals. While the klystron royalties were an important resource for the lab, Terman believed that government funding would be a less restrictive and substantially larger source of funding for building academic research programs. This marked a substantial change in attitude toward government sponsorship of research compared to the pre-war period. Prior to the War, universities wanting to remain free and independent in their educational mission had been highly critical and generally rejected government resources for support of research. Moreover federal funding in support of research was not channeled toward private universities. The Manhattan Project, work at the RRL and other government labs on university campuses during the war had changed that.

Terman developed what he termed "a recipe for distinction"[5] in building Stanford's Engineering School. The recipe contained two main ingredients: The Mainstream Theory—one should be strong in areas of mainstream interest and importance rather than in "niche" areas, even though one might be able to be the leader in esoteric areas. The second key component of Terman's recipe for success was to increase the science and engineering faculty in key areas where funding could be attracted—he called this his program for building "steeples of excellence." Terman pursued projects he thought could be "self-financing" and would generate their own momentum of sustained growth. To accomplish this Terman sought to get the very best talent he could. Rather than using government grants to increase salaries of faculty already on staff, Terman pursued what he termed "salary splitting." The strategy was to pay for half of the salary of a new faculty member from grants and contracts. Research associates and other personnel working on sponsored projects would be entirely covered from contract funds. In addition building expansions and equipment would be funded on contract.

Terman's goal was not just to bring money into the university. The primary goal was to build the premier research program in electronics (or other potential "steeples of excellence"). This was to be accomplished by obtaining the very best talents in the field and building a graduate program around them. Training of graduate students and the production of Ph.D.s was as important as any other component of the program. Students were to be brought into the research project as part of their graduate training. In his many public discussions of these ideas in the 1960s when he was asked to advise other areas on how to go about constructing their own recipe for success, Terman was insistent on the centrality of the research mission of the faculty. He was scornful of going after a contract for applied research and generally rejected such contracts unless they fit into the overall mission of increasing the prowess of the research component (more on this later). He was critical, for instance, of a number of universities he advised because they went after contracts that they could fulfill with mediocre talent. Rather than simply bringing in contract dollars Terman's goal was to get funding as a way to hire the best talent. Sponsored projects would then follow on the principle that the direction of research and development in the field was being set by the Stanford Electronics Research Lab.

If government funding provided the primary resource for Terman's program, building a connection to industry was equally critical. For Terman the key thing was to turn ideas into technology, and this required close collaboration with industry. Terman was also concerned about building an industrial base closely associated with the Stanford program. In presentations to engineering societies and various public forums Terman repeatedly insisted that the requirements for a career in engineering had changed since before the war.[6] Terman emphasized that engineers needed to be educated much more thoroughly in physics and advanced mathematics than previously, and he observed that technological complexity was advancing so rapidly that an undergraduate education would no longer suffice to prepare an engineer for the challenges of a career in industry. The requirements of modern industry were such that a master's degree or Ph.D. were becoming a prerequisite for many fields, particularly in complex and rapidly changing new fields of electronics and computers. To address this problem Terman developed Ph.D. programs with graduate fellowships funded by federal grants and contracts, and he took the innovative step of creating the so-called "Honors Cooperative Program" which allowed researchers and workers at local firms to complete advanced engineering degrees at Stanford.

In this knowledge-intensive environment, Terman believed the university would play a more central role than ever in the creation of new technology. He envisioned what he referred to as a technical community of scholars made up of local electronics firms in the Bay Area and the west coast with research facilities near Stanford staffed by Stanford-trained engineers. It would be a dynamic community where research in Stanford labs would find its way into industry through the training of students and consulting by the faculty. Stanford-originated technologies would find their way into the electronics industry as well, providing revenues for enhancing the research program. Terman also allowed for industry to bring its own problems for research to the university, and in fact he provided numerous ways for this to happen. But foremost in Terman's plan was that the university would be the center of the technical community providing innovations, training, and guidance. He explicitly sought to limit the influence of both the government and companies in defining the problems labs such as the SEL and the Hansen Lab would investigate. Terman sought to build trust among government and industrial sponsors of research in the technical directions pursued by the research faculty. By maintaining close relationships with the needs of government and industry through consulting and training of students the research faculty would naturally pursue projects of benefit to the sponsors as well as advancing the research mission. Thus instead of receiving research funds to pursue specific problems defined by a sponsor, Terman wanted both government and industry to invest funds in the research directions defined by the core faculty of the lab. Even in the case of industry funding, Terman rejected funds for specific applied industry problems in favor of funds to pursue a general research direction of interest to a company. The company funding the research would have privileged access but not exclusive rights to the research results.[7]

As plans for linking research labs with industry materialized an additional ingredient of Terman's "recipe for distinction" emerged. The idea of using Stanford land for commercial property that would bring income to the university was already well underway by 1950, having been proposed by Alf Brandin as a means for generating income to offset the ailing finances of the university. Work in the Microwave Lab under Felix Bloch had already resulted in the creation of Varian Associates by Russell Varian and Edward Ginzton. Founded in 1949, Varian Associates was the first occupant of what would become the Stanford Industrial Park. Terman interested several other electronics firms in following moving research facilities to the 450 acre sector of land designated for commercial development by the Board of Trustees in 1950. Included in this was development of the Stanford Shopping Center. In 1952 the decision was taken to set aside land in this sector for the Medical Center that would move from San Francisco to the Stanford Campus in 1958.[8]

An innovative feature of Terman's evolving program over the years was its tight coupling of teaching, research, and technology transfer through close working—particularly consulting—relationships with industry. Many examples of this successful strategy could be given, beginning with a long term relationship with General Electric that started in 1953. GE received contracts to produce several types of microwave devices, including klystron tubes. In addition GE was interested in the commercial development of radiological devices, particularly the medical accelerator being developed by Henry Kaplan and Edward Ginzton in the Stanford Microwave Lab. In his proposals to GE for establishing an advanced research electronics lab in the industrial park near Stanford, Terman gave a detailed exposition of Stanford's philosophy of linking research and development in electrical engineering and physics to industry.[9] The research program, Terman explained, was an outgrowth of the academic program and was closely coordinated with the instructional activities of the University, particularly in graduate training. "Initially," Terman wrote, "basic research projects are selected in the usual manner, simply on the basis of the extent to which they will add to the knowledge of the subject: but it has generally been found that practical applications of this knowledge are not long in forthcoming, and through the application of judicious assistance and planning along the way we have usually been able to produce, ultimately, not only equations and reports, but also practical devices embodying the principles involved."[10] Research projects were taken on in fields in which some faculty member had specialized competency, an arrangement that allowed faculty to function effectively both as teachers and research workers without undue inroads on their time. Research projects were frequently used as thesis assignments for graduate students, thus permitting Stanford to employ graduate students as members of the staff of the Electronics Research Laboratory while they were at the same time pursuing their work toward a graduate degree. A key part of the typical arrangement with research companies in the Stanford Industrial Park was that Stanford faculty, research associates, and technical personnel would provide instruction to the company researchers in the design, development and construction of linear accelerators (or other related electronics technologies) developed at Stanford. Faculty members relevant to the company research interests would also be appointed as Principal Associate Scientists to assist and advise the company research staff. Companies such as GE would license the Stanford patents on klystrons and medical accelerators relevant to their commercial plans.[11]

An equally important aspect of Terman's vision was that the synergy between Stanford and its industrial partners was not a one-way relationship. Stanford research programs should benefit from the knowledge and expertise housed in advanced programs in industry. Consulting relationships opened some of these doors, but teaching appointments of industry scientists at Stanford, and where possible the strategic hiring of entire teams of scientists from industry as Stanford faculty heading up their own teaching and research programs was viewed as a means to strengthen Stanford's research profile and insure it would have cutting edge faculty defining the frontiers of new technical programs. These new "steeples of excellence" would provide the competitive edge for acquiring federal funding for new projects in the sciences and engineering. The GE agreement, one of the earliest of these joint exchanges, was typical of a pattern repeated frequently in the intervening years at Stanford. In the GE agreement, for example, provision was made for certain GE personnel to teach one three-hour course at Stanford in any academic semester without remuneration. GE staff with teaching appointments at Stanford were allowed to advise thesis work of Stanford students.

Perhaps the most spectacular example of Terman's efforts to fertilize academic programs by absorbing advanced programs from industry is the development of the solid state physics program at Stanford. At the suggestion of his former student, David Packard the president and co-founder of Hewlett-Packard, Terman initiated the research and teaching program in solid state electronics at Stanford. Terman and Packard had watched the field of semiconductor electronics closely since the invention of the transistor by William Shockley, John Bardeen, and Walter Brattain at the Bell Telephone Laboratories in 1947. Terman and Packard viewed solid state electronics as one of the most promising fields in electrical engineering, and they wanted the university to build a major presence in this new field. Packard and his business partner, William Hewlett, were eager to transistorize their electronic measurement instrumentation business. They were also interested in producing semiconductor devices. Hewlett and Packard deemed it in their interest to support the development of solid state at Stanford. A solid state group at the university would act as a local resource for Hewlett-Packard and other electronics firms on the San Francisco Peninsula. It would also train engineers in the new technology. Hewlett and Packard expected to hire some of them.[12]

To build a dynamic program in solid state electronics, Terman hired John Linvill, a young engineer at the Bell Telephone Laboratories, in 1955. Linvill, an MIT Ph.D., had briefly taught on the MIT faculty before joining the technical staff of the Bell Telephone Laboratories. At Bell, he had made a name for himself by designing a new transistor-based amplifier which became widely used in local area networks. Terman liked Linvill's inventiveness and expected that his appointment would give Stanford access to Bell Labs' technology and scientific staff.[13] Packard assisted Terman in recruiting Linvill from the Bell Labs. He actively promoted the position to Linvill. To help the university match Linvill's salary at Bell, Packard offered him a consulting arrangement with H-P. Under the terms of the agreement, Linvill would give a series of lectures on transistors to H-P's engineering staff. Packard also impressed upon Linvill the importance of building close relations with local electronics firms—especially those in the recently created Stanford Research Park.[14]

Terman rapidly came to appreciate that Linvill was himself a superb academic entrepreneur—a steeple of excellence. In the next fifteen years, the two men closely collaborated on building the solid state program at Stanford. At Terman's urging, Linvill "transistorized" the electrical engineering curriculum and established the Solid State Laboratory, originally as part of Terman's Stanford Electronics Lab, focused on transistor circuit research, and heavily funded by the Office of Naval Research, IBM, and Texas Instruments.

A few years later, Linvill expanded the scope of the Solid State Laboratory to device physics and silicon processing. To do so, the Solid State Lab needed to acquire rare expertise in the fabrication of semiconductor devices which could be found in only a few corporations. Fortunately in late 1955 with Terman's urging, Shockley, the co-inventor of the transistor at the Bell Labs, moved to the San Francisco Peninsula to start his own semiconductor venture, Shockley Semiconductor Laboratory. Shockley's Laboratory specialized in the making of silicon devices. The establishment of the new Laboratory provided a wonderful opportunity for technology transfer—from Shockley Semiconductor to the university. Linvill and Terman asked Shockley whether they could dispatch a junior faculty member to his laboratory to work as Shockley's apprentice and learn about silicon processing. Shockley liked the idea. He needed Ph.D.s with a solid knowledge of semiconductor physics and expected that a strengthened solid state program at Stanford would supply the skilled workforce he needed. This was a critical agreement for the development of the solid state electronics program at Stanford.[15]

Linvill and Terman recruited Jim Gibbons, who had completed his Ph.D. with Linvill, to learn about silicon processing technology at Shockley. Gibbons' task was also to reproduce Shockley's lab on campus. This enterprise was funded again by the ONR.[16] Gibbons joined the Stanford faculty and the technical staff of Shockley Semiconductor in the fall of 1957. Sending Gibbons to Shockley Semiconductor was a judicious choice indeed. The firm specialized in silicon, the material that rapidly became dominant in semiconductor technology. Shockley Semiconductor was also teeming with talent. Shockley had hired an exceptional group of physicists and engineers—men such as Gordon Moore, Robert Noyce, Jean Hoerni, Jay Last, and Eugene Kleiner. These men later played a central role in the semiconductor industry in Silicon Valley. At Shockley Semiconductor, Moore, Noyce, and Kleiner introduced Gibbons to key processes in semiconductor fabrication such as crystal growing, lapping, solid state diffusion, and oxidation. Gibbons also got to know these men well. When eight staff members

(Moore, Noyce, Hoerni, Kleiner, Last, Julius Blank, Victor Grinich, and Sheldon Roberts) rebelled against Shockley and left the firm to start their own venture, Fairchild Semiconductor, they asked Gibbons whether he wanted to join the new corporation as its ninth founder. Gibbons, who was interested in an academic career, declined the offer. This later proved to be a poor financial decision as Fairchild Semiconductor established itself as a major semiconductor manufacturer and made its founders quite wealthy. But Gibbons had developed ties with key players in Silicon Valley. These ties later facilitated the growth of the solid state electronics program at Stanford.[17]

Rather than following the footsteps of the "Traitorous Eight," as Shockley called his deserter research staff, by starting a new semiconductor venture, Gibbons replicated Shockley's laboratory on the Stanford campus. In March 1958, Gibbons' Stanford laboratory fabricated its first silicon device, a four-layer Shockley diode. This was a substantial achievement. Most people who had heard of Stanford's plan to build a device processing laboratory thought that its success was very unlikely. Device research and fabrication had always been the province of industry. It was also widely argued at this time that device fabrication technology was too complex for a university to master. Gibbons proved that it could be done. In this example of "reverse technology transfer" Stanford was probably the first university in the United States to fabricate silicon devices. On the basis of this achievement, the ONR increased its already sizeable grants to the Solid State Laboratory.[18] Over the next two decades the Solid State Laboratory was the home to some of the most advanced research projects in computer engineering in the U.S., including most famously, the DARPA supported VLSI (Very Large Systems Integration) project that led to the commercial development of RISC (reduced instruction set computing), which revolutionized computer chip architecture and formed the basis of MIPS, and the Geometry Engine, the basis for Silicon Graphics, and the SUN workstation, all major contributions to the dynamic firm culture of Silicon Valley.[19]

I have outlined several key components of what emerged during the 1950s as Terman's "recipe for distinction"[20]:

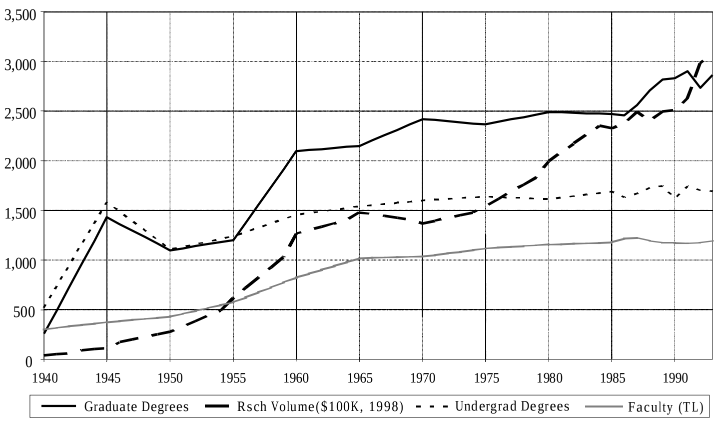
- Using government grants and contracts to finance "steeples of excellence"
- Salary splitting as a means to grow the faculty
- Concentration on graduate student research and production of MS and Ph.D. degrees

- The establishment of the Stanford Industrial Park[21] as a means to create profitable exchange relations between industry and Stanford research labs, particularly in areas of electronics
- The Honors Cooperative Program as incentive for companies to locate near Stanford and as a resource for supporting the teaching component accompanying the building of "steeples of excellence"
- Emphasis on licensing Stanford inventions and establishing faculty consulting relations as means for getting Stanford ideas into the core of industry

A number of quantitative indicators suggest the power and success of this "Terman Model." The impact of Terman's ideas on university finances and departmental growth are unmistakable. The following several charts provide an overview.

Consider first the strategy Terman initiated of focusing on government funded research grants and contracts as the way to grow the quality of university programs. Figure 1 below charts Stanford research volume, degrees and faculty from 1945-2000. What the figure suggests is that research volume is central to running the university, and that with Ph.D. production closely tracking research volume, Stanford is above all a research institution. Research dollars pay a very considerable portion of the bills at Stanford.

Figure 5. STANFORD RESEARCH VOLUME, DEGREES, AND FACULTY 1945-2000



Source: Charles Kruger and Stanford University Financial Reports. Figures exclude funding for SLAC.

In the 1950s and 60s the Engineering School accounted for the largest sector of government grants and contracts, and within the Engineering School, Electrical Engineering was the major recipient of government funding. A key objective of Terman's program was to use government funding to increase faculty and build research programs, particularly graduate programs in engineering. Indicators of the success of this enterprise are the growth of school and departmental operating budgets, and the percentage of those operating budget accounted for by outside funding; namely, from grants and contracts as opposed to tuition and endowment sources.[22] Certain patterns emerge from the information we do have that carry over into the post-1965 period. We present those patterns in Figures 2-4 and extrapolate to the 1950s based on sporadic data available to us for those years.

Figure 6. ENGINEERING SCHOOL SPONSORD PROJECTS COMPARED TO TOTAL OPERATING BUDGET

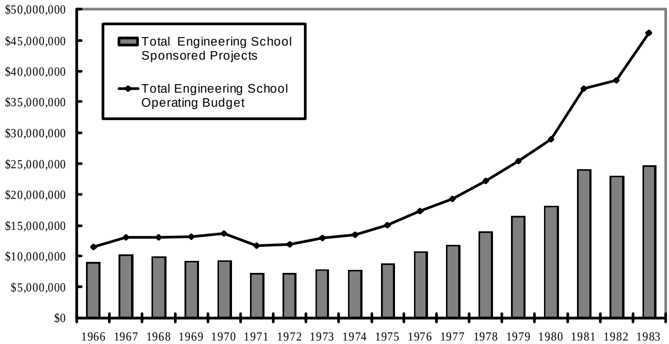


Figure 7. ELECTORICAL ENGINEERING SPONSORED PROJECTS COMPARED TO TOTAL OPERATING BUDGET

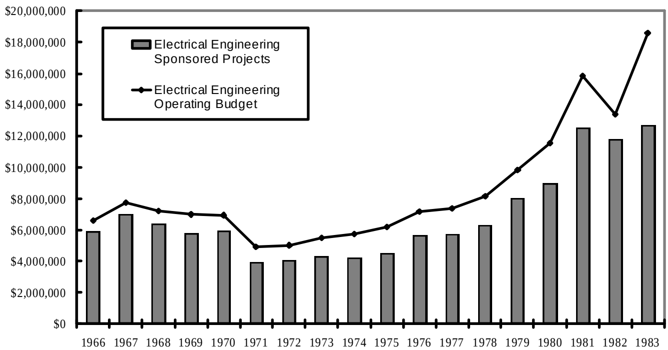
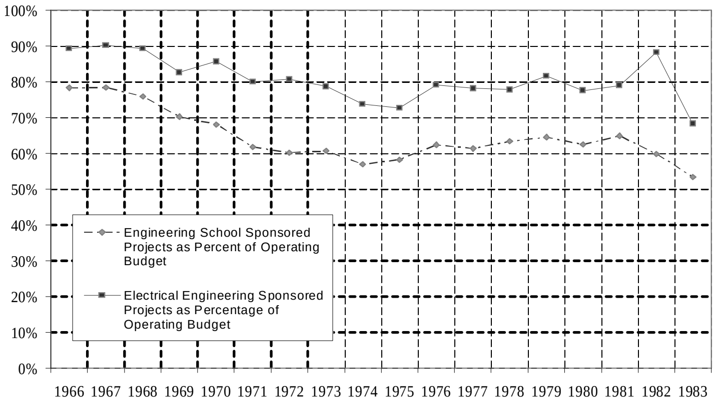


Figure 8. SPONSORED PROJECTS AS PERCENT OF OPERATING BUDGET: TOTAL FOR SCHOOL OF ENGINEERING COMPARED WITH ELECTRICAL ENGINEERING



What the data indicate is that in the Engineering School roughly 60% of the operating budget for the entire school was financed through grants and contracts. Terman's program started in Electrical Engineering and the major external funding resources came to that department. Hence it is not surprising to see an even higher percentage of the operating budget to be covered by grants and contracts. With the high around 90% reached in the mid-1960s and gradually falling to around 70% in the 1980s in the post-Vietnam period, we see roughly 80% of the operating budget for Electrical Engineering covered from grants and contracts. The sporadic data we have for the 1950s and early 1960s suggest that the percentage of the operating budget covered from grants and contracts hovered close to 90%. Indeed, when we shift our attention to the Hansen Labs for Applied Physics and the Electronics Lab we find anywhere from 90%-98% of the operating budget covered from grants and contracts over the period we have investigated. That in a nutshell was the Terman program.

Extending the Terman Model: Steeples of Excellence and Entrepreneurial Culture in the Medical School

The Terman model has been diffused within the Medical School as well. As noted above, in the immediate post-WWII years the financial condition of the

University bordered on a crisis situation. The financial situation facing the Medical School in those years was even worse, indeed, positively desperate. The physical plant of the Medical School, located in San Francisco, was in need of renovation and expansion. The School ran a deficit of approximately $400,000 per year, which had to be financed out of University funds. In 1950 President Sterling and the Board of Trustees appointed a Committee on Future Plans of the Medical School, headed by Professor Henry Kaplan, the Director of Radiology. During 1951-1952 the Committee interviewed and corresponded with faculty from the Medical School in addition to undertaking interviews with 20 medical leaders at other institutions. The work of the committee was distilled into a voluminous report. The most urgent needs the Committee identified were for major replacement and refurbishing of the Medical School physical plant and for annual financial support. They estimated that rebuilding the physical plant would cost ten to fifteen million dollars. To prevent the bleeding of general funds of the University for the annual Medical School operations would require new endowment of an additional fifteen million dollars. In plant funds and endowment, the total need was estimated at $30,000,000. The magnitude of the needed sum evoked the question: Would it be wiser to modernize and add to the existing Medical School facilities in San Francisco or to build anew on an alternative site? After more than a year of study the conclusion reached was embodied in the Board of Trustees' decision of July 15, 1953 to move the Medical School to the University campus.

As President Sterling commented in his foreword to the collection of speeches at the dedication ceremony of the new Medical Center in 1959 the basic reasoning given for this decision was that the future progress of the medical sciences would be inextricably linked with progress in the basic physical and biological sciences, and increasingly with the social sciences, such as psychology and sociology; therefore, Sterling concluded, "This key relationship of medical education and science to other scientific fields can best be strengthened and advanced by bringing the Medical School into the closest possible physical and intellectual relationship to the whole university."[23]

The move of the Medical School to the main campus was accompanied by a complete revision of the medical curriculum in which more basic science was introduced. The Stanford Program, as it was called, lengthened the period of medical education from four to five years and included substantial work in basic science as well as a significant exposure to laboratory training. In addition, the medical faculty became a so-called "full-time" faculty, shifting its base of support from clinical fees to funds provided by the University. Thus in moving to the main campus the Medical School faculty became essentially university faculty just like faculty in the Engineering School or in Humanities and Sciences, and along with this the emphasis of the new Medical Center was to shift in the direction of scientific medical research.

Sterling used the attention generated by the new science-based curriculum and the move to the Stanford campus to launch a major public relations campaign and fund-raising drive for the new Medical Center. In addition to a public fund-raising drive, a key part of this effort was Sterling's lobbying effort with Congress to get the Hill-Burton Act of 1947, which supported the expansion of American medical programs, to include the financing of buildings and other capital expenses. This new Hill-Burton Act was passed in 1956. Stanford was a major beneficiary of the new federal funding. Along with a large influx of federal funds to support the new initiative, Sterling was also successful in obtaining major Ford Foundation funding to support the transition of the faculty to full-time and the hiring of additional faculty for the new expanded Medical Center. Indeed, in a step signaling that the new Medical Center was heading in new directions, Sterling demanded that all heads of departments resign with the move to the main campus.[24] Two new departments were to be created in the move, the Department of Biochemistry and the Department of Genetics, housed not in the School of Arts and Sciences, but importantly in the Medical School.

In the midst of this major transition of the Medical School, Fred Terman became Provost in 1955. Terman's style of encouraging entrepreneurial activity meshed well with the initiatives already begun by Sterling, Alway, and Kaplan in reshaping the Medical School. Terman wasted no time in encouraging Medical School faculty to adopt his strategies for building programs with government funds. Similarly to his strategy for building the Engineering School, Terman emphasized the primacy of research. A letter to faculty member Walter Greulich was typical:

> When in my office, you stated that teaching duties in the Medical School normally took about half the time of a faculty member, and that the other half of his time was available for research. If one could have 50% of this research time charged against research contracts and grants, rather than carried by the regular budget, it would free enough salary money in the

> Medical School budget to raise all salaries by 33%. If all of the research time could be charged to research contracts (which is probably an impossibility although nearly true in Engineering) it would free enough salary money to double salaries.
>
> Since the idea of having the government or foundation pay for the services that it receives credit for would seem entirely legitimate and is certainly not immoral, I suggest this method of aiding the finances of the Medical School be taken advantage of whenever possible. [25]

As Provost, Terman encouraged faculty to be aggressive in their pursuit of federal funding and scrupulous in accounting for the research-related costs of their work.[26] He held frequent meetings with deans and other University administrators explaining the elements of his "recipe for distinction" and his strategies for using salary-splitting and gift funds from corporate sponsors to expand the research faculty. The initial efforts were not easy. Terman encountered resistance by some faculty who thought federal funding should be avoided in order to remain independent, and his policies were opposed by critics concerned that the primary occupants of the Industrial Park were companies funded by military contracts. He sought to disarm such critics by seeking to attract companies in biomedical sciences into the research park. But Terman's most important strategy for building an environment that supported entrepreneurial activity was in hiring faculty with similar incentives as his own to build a powerful infrastructure to support their research programs. Perhaps the most striking success of Terman's efforts at building an entrepreneurial culture during his Provost years was in building the new science departments of the Medical School.

In Henry Kaplan, Terman and Sterling had at least one colleague in the Medical School who appreciated and enthusiastically endorsed the reorientation toward federally funded research programs. Kaplan had been trained in the emerging field of diagnostic and radiation therapy at the University of Minnesota, where he acquired a solid background in physics en route to receiving his master's degree in radiology. Convinced that improvements in cancer therapy would only come from joining laboratory research and clinical investigation, Kaplan launched a project on the pathogenesis and induction of leukemia. After a brief period as assistant professor at Yale and a one-year stint at the National Institutes of Health in Bethesda, Maryland, Kaplan joined the Stanford Medical School in 1948 as head of the two main department of radiology.

In addition to his investigations into the causes and treatment of leukemia Kaplan concentrated on Hodgkin's disease, and several other types of cancer. In 1950 Kaplan was experimenting with using high voltage x-ray radiation as treatment to cure patients, but he quickly became unhappy with the x-ray machines available, which concentrated the radiation on the patient's skin rather than penetrating to deep-seated tumors. In the fall of 1951 Kaplan learned about the work on the early linear accelerator being conducted at the Stanford Microwave Lab directed by Edward Ginzton, and he arranged a meeting with Fred Terman, Ed Ginzton, and Leonard Schiff, the chair of the Physics Department on the Stanford campus to explore the prospects for using the linear accelerator to create highly focused directed radiation. Ginzton and other members of the Microwave Lab were interested in exploring the potential biological and medical applications of microwave physics, nuclear magnetic resonance, and x-ray microscopy, so that Kaplan's proposal met a welcome audience. Ginzton and Terman were also on the Board of Varian Associates, recently formed to exploit Stanford patents in nuclear magnetic resonance and advanced microwave devices, and they knew Varian Associates was interested in developing medical instrumentation as well. Thus began a multi-year collaboration between Kaplan, the Stanford Physics Department, various members of the Stanford Linear Accelerator staff, the Microcrowave Lab, and Varian Associates to develop the clinical medical accelerator and determine standardized dosimetry measurements to provide therapists with accurate information on the absorbed doses of radiation at different depths with the patient's body. To support the collaboration Kaplan and Ginzton received grants from the American Cancer Society ($100,000), the U.S. Public Health Service ($113,000), and the James Irvine Foundation in San Francisco ($75,000). The first successful clinical medical accelerator was constructed at the Microwave Laboratory and installed in the Stanford University Hospital in 1957, and shortly thereafter physicist Greg Nunan at Varian Associates was able to transform the prototype into a compact prototype medical device for medical treatment. Nunan and Karl Leslie Brown led efforts at Varian to develop the Clinac, the first successful commercial version of which was brought to market in 1972.[27] In 1961 Kaplan received funding of $945,000 with additional funding of $600,000 per year for six years from the NIH to establish the Clinical Radiotherapy Cancer Research Center at the Medical School to support research and treatment with the medical linear accelerator. In this facility Kaplan and his colleagues did path breaking work in establishing standardized therapy protocols for treatment of several cancers. Perhaps Kaplan's most important work was in the treatment of Hodgkin's disease, with which he was able to achieve astonishing cures of over 90% in Stage I and Stage II Hodgkin's disease with a 79% survival rate over five years.

From this brief profile of Kaplan's early research collaboration with the Microwave Lab and Varian Associates in developing the clinical medical accelerator (Clinac) during the early 1950s, it is evident why he was among the loudest voices seeking to transform the fundamental clinical orientation of the Stanford Medical Center by moving it to the main Stanford campus where it would acquire a research focus through the establishment of strong ties to the basic research sciences. Kaplan completely shared Terman's views about seeking federal funding to build research programs. Indeed in the spirit of Terman's "salary splitting" strategy for adding faculty strength with research grants, the first round of grants Kaplan and Ginzton received for the development of the clinac supported the four physicists Michael Weissbluth, C.J. Karzmark, R.E. Steele, and A.H. Selby, who joined the medical accelerator project to determine dosimetry measurements. As head of the committee to advise Terman on the appointment of faculty to lead the Medical School in its new research orientation, one of Kaplan's first recommendations was to hire Arthur Kornberg.[28] Negotiations began with Kornberg in 1957. Kornberg was the Director of the Department of Microbiology at Washington University, St. Louis, where he had been since 1953 following a move from the NIH. At Washington University Kornberg had already assembled a stellar cast of young biochemists and molecular biologists, including Paul Berg, David Hogness, Robert Lehman, Melvin Cohn, and Dale Kaiser. Kornberg and his colleagues also had an extremely impressive track record of Public Health Service grants for supporting their research. Kornberg negotiated with Terman and Alway to move the entire department to Stanford beginning in 1959. This was a major coup for the new Medical School, for in the months following his initial acceptance of the Stanford offer, Kornberg received the Nobel Prize for his work on the replication of DNA. Kornberg not only moved most of his staff to Stanford but was also successful in being awarded more than $500,000 in Public Health Service grants to equip his new Stanford laboratories.

As part of his negotiations for building biochemistry, Terman encouraged Kornberg to propose potential faculty for other departments that would complement the strengths in biochemistry, and he invited Kornberg to serve on the search committee for the chairmanship of the Chemistry Department. Kornberg immediately proposed bringing Joshua Lederberg to Stanford. Lederberg, who had been awarded the Nobel Prize in 1958, accepted the offer and left Wisconsin to form the new Genetics Department at the Stanford Medical Center in 1959. At Stanford Lederberg wasted no time in building a program in molecular medicine with matching grants of $1 million each from the Rockefeller and the Kennedy Foundations to support construction of facilities for the Kennedy Center for Molecular Medicine in 1962.

Lederberg also received a $500,000 grant from NASA in support of work on planetary biology that year, a project that eventuated in the ACME computing facility and later the SUMEX computing facility. For the purposes of the present study, one of Lederberg's most significant contributions to the new orientation in the Medical School was his establishment of the Biomedical Instrumentation Research Laboratory, funded by the NASA Exobiology program to support the development of an automated lab for the Mars Viking Lander missions. Lederberg, Carl Djerassi, and computer scientist Edward Feigenbaum created the first expert system, DENDRAL which was designed to analyze soil samples scooped up by a robot and run through a mass spectrometer to determine if there are organic molecules on Mars capable of supporting life. Lederberg hired Elliott Levinthal to direct the Biomedical Instrumentation Research Lab. Levinthal had done his Ph.D. in physics at Stanford with Felix Bloch, doing pioneering work in the field of nuclear magnetic resonance. After completing his Ph.D. in 1950 Levinthal became the first director of research at Varian Associates. In the mid-1950s he left Varian to start his own company, Resonex, a medical and surgical instrumentation company in Fremont, which he ran until Lederberg convinced him to return to Stanford in 1962 as director of the instrumentation lab.

Another key appointment Lederberg made to the Genetics Department was Leonard Herzenberg. Herzenberg had received his Ph.D. in biochemistry and immunology from the California Institute of Technology in 1955, which he followed with a postdoctoral fellowship from the American Cancer Society to conduct research at the Pasteur Institute in France before returning to the U.S. in 1957 to take a position at the Public Health Service at the National Institutes of Health. Herzenberg joined Lederberg as assistant professor of genetics at Stanford in 1959.

Herzenberg and his lab have also become the stuff of legend at Stanford. In his early years at Stanford Herzenberg's lab began researching the interaction of lymphocyte cells in the immune response and in the genetics and biology of lymphatic tumors. They recognized the need for a method for isolating various kinds of lymphocytes, many of which differ only by small surface differences. Ideally they wanted to isolate variants of cultured single cell lines that differed from the parent cell line only by the loss or gain of a single receptor structure on the surface of the cell. A number of researchers were beginning to tag cell surfaces with fluorescent markers, enabling them to identify variants of cells quite precisely with the aid of a fluorescence microscope. Herzenberg, however, wanted not only to identify fluorescence-tagged cells, but also to be able to isolate these cells. Herzenberg presented the problem to William Bonner and Russel Hulett of the Biomedical Instrumentation Research Lab. About this same time, in the early 1960s, Richard Sweet from the Stanford Applied Electronics Lab was working on high-speed computer recording methods for an ink-jet printer for which Sweet, in 1965, pioneered the technique of independently deflecting droplets of electrostatically charged ink at the rate of 200,000 droplets per second. With funding from the NIH, Herzenberg, Bonner, Hulett and Sweet adapted these tools to fluorescence cell sorting.[29] In their prototype FACS, cells stored in a liquid reservoir were passed single-file through a small area illuminated by a green or blue laser beam operating at a wavelength selected to excite fluorescence in cells tagged with the appropriate fluorescent material. Since cells of differing types will have more or less fluorescent material bound to them, they will generate different charges on a photomultiplier proportional to the number of fluorescent molecules on each cell. By pre-selecting the amplitude of fluorescence corresponding to a desired cell class, the cells specifically sought could be separated from the mixture. To accomplish this, FACS put the desired cells in a droplet which would then be electrostatically charged positive or negative, so that it could be deflected to an appropriate reservoir, much in the same way that electron beams are deflected in a cathode ray tube. In order to select desired cells, the fluorescent light, filtered to remove the exciting wavelength was focused onto a photomultiplier tube. A second signal, related to the volume of the cell, was also generated by detecting the light scattered out of the illuminating beam. The two signals were then processed and combined to trigger an electric pulse charging generator which served to charge the liquid stream at the moment the droplet containing a desired cell was forming. The prototype would sort cells at a rate of 5,000 per second with a sample purity of between 90-99 percent.

From the mid-1960s through 1972 the FACS project was supported by NIH grants. In 1972 a patent was granted to Stanford, and it became one of Stanford

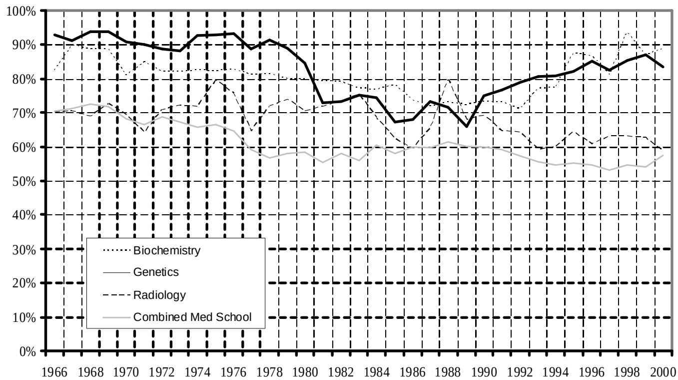
OTL's earliest licenses. From 1972 until 1991 the FACS was licensed to Becton Dickinson Immunocytometry Systems of Palo Alto. The Herzenberg lab worked closely with Becton Dickinson engineers in transferring FACS technology to industrial development. More than 30,000 FACS systems were operating in labs around the world as of 2002.[30] With revenues totaling nearly $30 million over its lifetime, FACS became one of the top three OTL patents.[31]

The examples of the Kaplan, Lederberg, and Herzenberg labs underscore the extent to which the Terman model was embraced by the new breed of medical scientists chosen to reshape the Stanford Medical Center. A key element of their success was not only in obtaining federal funding to support their work, expand their faculty and research teams, but in their interest in pursuing the development of instrumentation and therapies that grew out of collaborative efforts with the advanced laboratories of the physics, engineering, and computer science departments—the very sort of interdisciplinary collaboration and cross-fertilization that Sterling, Alway and Terman argued would shape medical science in the late twentieth century. As we have seen Kaplan worked closely with Edward Ginzton and the Microwave Lab, as well as with Varian scientists and engineers in building (and later marketing) the CLINAC. The Instrumentation Research Laboratory Lederberg founded was led by a Stanford physicist Ph.D. with a distinguished career in industry. When the Herzenberg group turned to them for assistance in developing the fluorescence activated cell sorter, it is not surprising that they looked to the Applied Electronics Research Lab for ideas and collaborators. Moreover, the development of FACS by Becton Dickinson inaugurated just the sort of connection to industry Terman had advocated; namely a long-term relationship in which the company continues to work with Stanford in developing additional technologies. Since its initial licensing of the FACS in 1972 Becton Dickinson has licensed more than 20 other technologies in the immunochemistry field.[32]

From their inception the Departments of Biochemistry and Genetics have been hotbeds of innovation in the field of molecular genetics and molecular medicine, and they have been major sources of the biotech revolution in the Bay Area from the 1980s to the present. This movement has been so important that is worth considering it a new phenomenon parallel to the Silicon Valley phenomenon that we might call "Biotech Valley." Aggressive pursuit of federal funding combined with careful cultivation of relationships to industry have been key elements of the entrepreneurial strategy of both departments. Federal grant awards to the Biochemistry Department were approximately $582,000 in 1966. In 1975 they topped $1 million, and reached $2.24 million in 1982, $3 million in 1987, and $4 million in 1993. The Genetics Department enjoyed even greater success in this same time period: Federal grants to Genetics totaled approximately $740,000 in 1966, surpassing the $1million mark to $1.75 million in 1974, $2 million in 1978, $3 million in 1990 and due to the influx of funding from the Human Genome Initiative exceeded $6 million in 1993. In 1974 and 1975 these two departments combined accounted for 20% of the federal grant dollars received by the Medical School, and on average during the period 1966-2000 these two departments accounted annually for 6.6% (Biochemistry) and 7.6% (Genetics) of the federal grant dollars awarded to the Medical School.

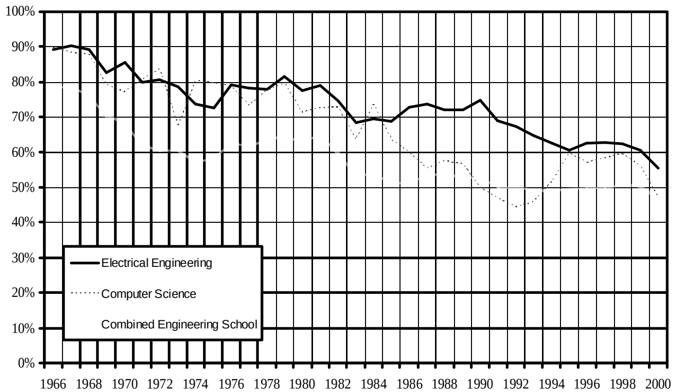
The departments of radiology, biochemistry, and genetics all fit the Terman model in the style of their growth. As prime recipients of government funding, particularly from the NIH and NSF, these departments were the first medical school departments to finance their growth and operating budgets almost entirely from government grants (Figure 7). They also evolved important relations with industry and made extensive use of the Honors Cooperative Program in building teaching components of their programs directly linked to the emerging biotech industry. When compared with major Engineering School departments Electrical Engineering and Computer Science, illustrated in Figure 8, it is clear that very early on into its formation, the Terman model had made a major impact in shaping the Medical School.

Figure 9. PERCENTAGE OF TOTAL OPERATING BUDGET COVERED BY SPONSORED PROJECTS FOR THREE MEDICAL SCHOOL DEPARTMENTS



Source: ***Stanford Annual Reports.***

Figure 10. PERCENTAGE OF OPERATING BUDGET COVERED BY SPONSORED PROJECTS FOR TWO ENGINEERING SCHOOL DEPARTMENT



Source: ***Stanford Annual Reports.***

Conclusion: Federally Funded Innovation Cycles

A claim frequently asserted about researchers in biotech, materials science, computer science, electrical engineering, and other potentially financially rewarding fields at elite research universities is that they are forcefully encouraged by the leadership of their universities to become the handmaidens of industry by selling their inventions in order to finance their research as well as lured by personal financial gain. In the case of Stanford this push to commercialize faculty research, so the argument goes, goes back to the early Post World War II era bargain Terman struck with the incipient military-industrial complex. I want to conclude with some reflections on how significant and important the licensing of its inventions is to Stanford. How important is this activity? Should Stanford researchers be engaged in these entrepreneurial activities? Why do it?

Here are some facts to conjure with: During its activities from 1970-2003 the Stanford OTL has generated a cumulative total of nearly $595 million; it has received 5,324 invention disclosures; and it has patented 1,371 inventions. As we have seen, the total research costs in 2002 exceeded $400 million. Thus, while Stanford has been extremely successful in generating revenues from licensing its inventions, the sum total of that activity is relatively small in comparison with the research needs of the university taken as a whole. The average over the period 1990-2000, for example, has been approximately $40 million per year. I am by no means asserting that licensing revenue is trivial, but the returns are relatively small compared to the costs of current research, and the potential ramifications to other dimensions of university culture and the mission of higher education are arguably high.[33]

So why pursue a vigorous technology licensing program aimed at the commercialization of university research? Obviously one can always hope to score one or several Cohen-Boyer patents that bring in revenue to support the work of an innovative program. But at Stanford since the days of Frederick Terman the primary answer to that question has been that interaction with industry produces cutting edge science that is not only economically relevant but enhances Stanford researchers' competitive edge in winning federal funding, the main plum in the game. Central to this approach was the notion that first began to dawn on Terman during his stint as director of the Radio Research Lab at Harvard during World War II that in the post war era the nature of science was going to change inalterably; that it would no longer make sense to distinguish so radically between pure and applied research and that the boundaries between basic research and development were going to erode just as certainly as the boundaries between science and technology were being redefined. In such an environment encouraging appropriately defined partnerships with industry was the path to recruiting and retaining the most talented faculty, and in the end, the path toward producing the kind of science and engineering that would be rewarded with federal grants and contracts.

In addition to catapulting Stanford from its marginal backwater status in the immediate post-War period into the top ranks of research universities almost overnight, Terman's steeples of excellence program succeeded in building a faculty of star academic researchers in a number of fields in engineering, biomedicine, and the mathematical and physical sciences. Perhaps the most important legacy of this program, however, was the creation at Stanford of an administrative environment and institutional culture highly supportive of entrepreneurial activity. This point is frequently misunderstood to mean that Stanford and similar entrepreneurial institutions encourage their faculty to seek industry sponsorship and government contracts that make the institution a handmaiden to industry and the military-industrial complex. The supposed goal of encouraging this entrepreneurial activity on the side of the administration is to generate income for the university. I have tried to argue that Terman resisted this approach and instead set his sights on going after research dollars and government contracts that supported basic research. He steadfastly resisted programs that tied any of his departments to a specific company (which he thought would ultimately reduce the flow of resources into the university and limit the impact of Stanford research programs) or to applied work for the military (as much as he appreciated funding from the defense departments). The attitude Terman cultivated was that highly motivated scientists and engineers should not be prevented from seeing their ideas and technologies materialized in industry. Terman’s view, a view that has been shared by every Stanford administration to the present and has become institutionalized as part of the culture, is that highly motivated scientists and engineers will simply want to see their work transferred to industry or to the clinic and that creating barriers to this activity would dissuade them from staying at Stanford. Ultimately the encouragement of industrial entrepreneurial activity—which in policy and practice at Stanford has been more of an effort not to create roadblocks to this sort of activity rather than explicitly requiring or strongly encouraging it—was viewed as a faculty and staff retention issue rather than a source of income to the university. The income would be generated by pursuing research grants and contracts. Highly motivated research engineers and biomedical scientists, in Terman’s view, are interested in technology transfer because they want to make a difference in society. They are also motivated by financial reward, but what persuades them to remain at the university rather than moving to industry is the opportunity to continuously expand and develop their research horizons in collaboration with colleagues and students and supported by institutional structures that facilitates the transfer of technology.

The case studies I have presented are just a representative sample of material from a larger study I have recently completed with Nathan Rosenberg, Henry Rowen, Christophe Lécuyer, Jeannette Colyvas and Brent Goldfarb that illustrates and confirms the continued relevance up to the present time of Terman’s vision and the strategies he pursued. Federal funding continues—by a very large margin—to be the primary source of research funding at Stanford, and indeed of funding for the university. Detailed study of the operations of departments that are the “hot-spot” pockets of innovation within Stanford are the ones supported by federal funding. This funding supports innovation in several key academic research units in the medical and engineering schools as well as some research units in the basic science departments, particularly chemistry and applied physics. The large number of invention disclosures and significant involvement of graduate students and faculty in technology transfer underscore the encouragement the Stanford administration and the OTL have invested in supporting a rich entrepreneurial culture in which cross-school and cross-disciplinary collaboration thrives particularly between elements of the engineering and medical schools. The view that Terman and his successors have fostered is that industry is both a source for employing students and for developing the technologies envisioned in Stanford research labs. But they have also viewed affiliation with industry through consulting relations and other forms of interaction as invaluable sources for stimulation of theoretical ideas and new research problems. This attitude found enthusiastic confirmation in areas of materials science, electrical engineering, and computing, and was significant in the early development of Silicon Valley.

Despite the important contribution made by Stanford scientists in areas of genetics, biochemistry, and applications of computer technology in the early years of the biotech revolution, Stanford biomedical scientists such as Henry Kaplan, Arthur Kornberg, Paul Berg, Joshua Lederberg, and Leonard Herzenberg were at first resistant to getting into the development of Silicon Valley-styled startup firms and other forms of industrial biotech involvement, fearing it would divert the advanced research directions they were pursuing and diminish their competitiveness for federal funding.[34] Since the late 1980s that attitude has been reversed, in large part due to the recognition of opportunities for more rapidly advancing their scientific programs. Confirmation for the positive effect of research collaboration with industry in enhancing the productivity of biomedical scientists has been provided by recent studies of "star scientists" by Zucker, Darby, and Armstrong. Their work argues that "star scientists" involvement with biotechnology firms appears to play a major role in determining which firms utilizing breakthrough discoveries will be most successful. Moreover, they demonstrate that these scientists often publish more and better science during the period they are involved with firms, apparently due to the greater resources which result from their commercial activities.[35] My interviews with Stanford biomedical scientists support the findings of Darby and Zucker. Rather than viewing income from technology licensing as necessary for raising the large funds necessary to pursue the research mission, licensing revenue data should be viewed as a reflection not only of successful technology *transfer* of Stanford research findings *to* industry, but also as a marker of Stanford's success in facilitating and fostering fruitful *relationships* with firms. These exchanges are reflections 1) of

Stanford success in the creation of a product that is of commercial (and in many respects social) importance, and also 2) of the successful interaction of Stanford researchers with industry counterparts in the transfer of their inventions (often playing more formal roles as consultants and advisors). Moreover, paying attention to industry as sources for interesting scientific and engineering research questions helps generate adaptation and co-evolution of Stanford research and industry, particularly the industry of Silicon Valley, a process which in turn continues to sustain Stanford's entrepreneurial spirit. During the late 1980s and 1990s Stanford biomedical scientists discovered what their colleagues in engineering and the physical sciences had learned from Terman: licensing and technology transfer is really a two-way exchange in which important 'cross-pollination' of knowledge, ideas, and practices takes place.

Notes

1 Thomas Byers, Robert Keeley, Anthony Leone, George Parker, "The Impact of a Research University in Silicon Valley: Entrepreneurship of Alumni and Faculty," *Journal of Private Equity*, Winter 2000.

2 James Gibbons, "The Role of Stanford University: A Dean's Reflections," in Chong-Moon Lee, William F. Miller, Marguerite Gong Hancock, and Henry S. Rowen, eds., *The Silicon Valley Edge: A Habitat for Innovation and Entrepreneurship*, Stanford; Stanford University Press, 2000, 200-17, especially 204-05.

3 See National Association of College and University Business Officers, 2003 Endowment Study Results,5 February 2004, <http://www.nacubo.org/documents/research/FY03Institution Listing ForPress.pdf>.

4 See NSF data compiled on Federal Funding of Research and Development.

5 Frederick Terman, Recipe for Distinction, notes for Terman's successor as dean of engineering <http://www.stanford.edu/dept/HPST/TimLenoir/Startup/TermanPapersSC160/SeriesIIIBox19/fol6/RecipeForDistinction.pdf>.

6 Electrical Engineering Curricula in a Changing World, 1956 <http://www.stanford.edu/dept/HPST/TimLenoir/Startup/TermanPapersSC160/SeriesVIIIBox1/fol9Speeches1955/ElecEngChangingCurriculum1956.pdf>.

7 A number of studies, particularly those of William Stuart Leslie and Rebecca Lowen have depicted Terman as basically selling the university to the military and industry. This picture does not stand up under close scrutiny. Terman, like nearly every other university administrator, sought government funding for academic programs as the only serious financial option for program building. Terman's own "recipe for distinction" was based explicitly on the university controlling the re-

search agenda and being deeply involved in setting research priorities.

8 The Stanford Industrial Park was the area of land bordering on California Avenue, Page Mill Rd, El Camino Real and a sector along the Foothill Road extension of Serra up to Arastadero Rd.

9 Terman to Oldenfield, 8 April 1954, Terman Papers, SC 160, Series II, Box 18, folder 8 <http://www.stanford.edu/dept/HPST/TimLenoir/Startup/TermanPapersSC160/SeriesIIBox18/fol8/Terman-Oldenfield8April1954.pdf>.

10 *Ibid*., 6.

11 *Ibid*., Exhibit A, 4.

12 David Packard, *The H-P Way: How Bill Hewlett and I Built our Company* (New York: Harper Business, 1995).

13 When Terman recruited Linvill from the Bell Labs, he followed a well-established practice. Most universities and corporations eager to enter the field of solid state raided the Bell Telephone Laboratories in the 1950s and the early 1960s. Texas Instruments and Motorola hired Bell Labs physicists and chemists to build up their semiconductor business. Harvard, Berkeley, and other universities also recruited their faculty members in solid state from Bell.

14 Frederick Terman to R. Holt, 11 March 1953, in SC160, series II, box 15, folder 22; John Linvill, oral history interview, 5 May 1987, Tape SV5, Stanford archives and special collections; Linvill, oral history interview conducted by Christophe Lécuyer, 25 April and 30 May 2002; James Gibbons, "John Linvill—The Model for Academic Entrepreneurship," *The CIS Newsletter*, Fall 1996. See also Leslie, *The Cold War and American Science*, 71-75.

15 In 1956, Linvill received a $13,600 grant from IBM. Texas Instruments also gave $11,625 for transistor circuit research. Terman to William Shockley, 20 September 1955, in SC160, series III, box 48, folder 8; Linvill to R. Wallace, 20 September 1955, in SC160, series III, box 48, folder 8; Linvill, "Excerpts from Lecture for Stanford Alumni in Los Angeles: The New Electronics of Transistors," 15 February 1956, in historical files of the *Campus Report*, folder: John Linvill; Linvill, "Description of Research Projects on Transistor Applications Undertaken in Summer 1955 under Task 7," 27 June 1955, in SC160, series II, box 15, folder 21; Gibbons, oral history interview conducted by Christophe Lécuyer, 30 May 2002.

16 Stanford received a $35,000 grant from the ONR to set up the laboratory.

17 Gibbons, "John Linvill—The Model for Academic Entrepreneurship;" Linvill, oral history interview conducted by Christophe Lécuyer, 25 April and 30 May 2002; Gibbons, oral history interview conducted by Christophe Lécuyer, 30 May 2002. For Fairchild Semiconductor, see Lécuyer, "Fairchild Semiconductor and its Influence," in Chong-Moon Lee, William Miller, Marguerite Hancock, and Henry Rowen, eds., *The Silicon Valley Edge: A Habitat for Innovation and Entrepreneurship* (Stanford: Stanford University Press, 2000), 158-83.

18 Linvill, "Application for Equipment Funds for Semiconductor Device Research," 25 February 1957, in historical files of the *Campus Report*, folder: John Linvill; Terman to William Cooley, 6 ducted by Christophe Lécuyer, 25 April and 30 May 2002; Gibbons, oral history interview conducted by Christophe Lécuyer, 30 May 2002. March 1958, in SC160, series V, box 7, folder 7; "Solid-State Devices Lab Tackles Silicon Transistors in Partnership with Industry," June 1958, in

historical files of the *Campus Report*, folder: John Linvill; Terman to Joseph McMicking, 25 June 1963, in SC160, series III, box 48, folder 8; Gibbons, "John Linvill—The Model for Academic Entrepreneurship;" Linvill, oral history interview conducted by Christophe Lécuyer, 25 April and 30 May 2002; Gibbons, oral history interview conducted by Christophe Lécuyer, 30 May 2002.

19 These developments are too expansive to cover in the current context. They are treated in the book-length study from which this paper is drawn.

20 From the points below I have omitted the important "industrial affiliates programs" initiated by Terman through which firms had access to research results and participate in conferences and workshops of special interest to their firms in exchange for an annual financial contribution to the research lab or sponsoring department.

21 Later known as the Stanford Research Park, which is the name it carries today (2004).

22 It is difficult to obtain records that would permit a breakdown of department operating budgets and sources of income before 1966. In that year a change was made in the reporting of Stanford accounts in the Annual Financial Report of the university that enable us to track sources of income for individual departments. From 1950-1965 the practice was too simply to list the total for grants and contracts and report individual grants as line items in a general ledger rather than listing them by department and school. Hence it is difficult to extract the information we are seeking. This is not to say that data is unavailable for the period between 1950-1965, but Special Collections does not have a systematic and complete holding of the financial records of individual departments for those years.

23 *Medical Care, the University, and Society*. Speeches Delivered at the Dedication of the Stanford Medical Center, 17 and 18 September 1959. Stanford; Stanford University Press, 1959, 3.

24 Spyros Andreopoulos. "Stanford University Medical Center. 25 Years of Discovery." *Stanford Medicine*, Fall 1984, 3-4. Also see *The Alway Years, 1957-1964*, published by Stanford University School of Medicine, 1964.

25 *Ibid*.

26 See for instance Terman's memo to Dean Robert Alway, 19 January 1962, Terman Papers SC160, Series III, box 43, folder 1:

> I understand that you and your staff have recently developed a consensus in favor of charging faculty salaries to research grants, to the extent consistent with the time devoted to such grant-supported research and with the overall funding of research, instruction, and service. I heartily approve of this policy and of its long-run contribution to the financial well-being of the school.
>
> I would, therefore, suggest that full consideration be given to the use this year of an appropriate portion of the NIH general research support grant for faculty salaries which otherwise would be charged to university general funds.
>
> I understand that it is NIH policy that any institutional funds which may be released by the use of the general research support grant will continue to be used for the direct costs of research or research training. I am sure that there must be substantial research and research-training

related expenses in the medical school on which any recovered salary dollars could be spent within the spirit of the policy.

27 Karl Leslie Brown entered Stanford in 1947 as a transferring senior and eventually earned his BS, MS and Ph.D. degrees in Physics. Brown was a member of the core team of young scientists who under the leadership of W.K.H. Panofsky designed and built the two-mile Stanford Linear Accelerator. Brown acquired an international reputation as an expert in beam optics for particle accelerators. As a graduate student in the 1950's, he was also part of the research team at Stanford that built the first ever linear accelerator to be used for cancer treatment, in close collaboration with Henry S. Kaplan M.D. of the medical school. Almost twenty years later, Karl L. Brown initiated and led the development of the first commercially successful line of such devices (named the CLINAC) by Varian Associates. Brown subsequently joined the Stanford faculty in 1974. He remained at Stanford throughout his career, except for several years of leave during which he participated in accelerator projects at laboratories around the world. Brown died in 2002.

28 At this time Kaplan had the offer of the chair of radiology at Harvard and he threatened to leave Stanford if Alway and Terman did not succeed in getting Kornberg or someone comparable to join the effort to restructure the medical school. Certainly the support Kaplan received from Ginzton, Schiff and others in the physics and engineering departments at this time, urging Terman to do whatever it took to retain Kaplan, provided additional impetus to the plans for the medical school.

29 Hulett, H.R., Bonner, W.A., Barrett, J. and Herzenberg, L.A. (1969). "Cell sorting: automated separation of mammalian cells as a function of intracellular fluorescence." *Science* 166 (906): 747-49; Merrill, J.T., Veizades, N., Hulett, H.R., Wolf, P.L. and Herzenberg, L.A. (1971). "An improved cell volume analyzer." *Review of Scientific Instruments* 42 (8): 1157-63. Bonner, W.A., Hulett, HR., Sweet, R.G. and Herzenberg, L.A. (1972). "Fluorescence activated cell sorting." *Review of Scientific Instruments* 43 (3): 404-09; Hulett, H.R., Bonner, W.A., Sweet, R.G. and Herzenberg, L.A. (1973). "Development and application of a rapid cell sorter." *Clinical Chemistry* 19 (8): 813-16; Herzenberg, L.A. and Sweet, R.G. (1976). "Fluorescence-activated cell sorting." *Scientific American* 234 (3): 108-17.

30 Herzenberg, L.A., D. Parks, B. Sahaf, O. Perez, M. Roederer and L.A. Herzenberg (2002). "The History and Future of the Fluorescence Activated Cell Sorter and Flow Cytometry: A View from Stanford." *Clinical Chemistry* 48 (10): 1819-27.

31 See Stanford Office of Technology Licensing, *Annual Report*, 2001-2002, 5. The top three OTL patents have been the Cohen-Boyer recombinant DNA patent, the Yamaha Sounds patent, and the FACS patent.

32 *Ibid*.

33 See Derek Bok, *Universities in the Marketplace: the Commercialization of Higher Education*, Princeton; Princeton University Press, 2003.

34 This theme is explored in depth in the larger study upon which I am drawing here. Space limitations has prevented me from expanding upon it here.

35 Lynne Zucker and Michael Darby, "Star Scientists and Institutional Transformation: Patterns of

Invention and Innovation in the Formation of the Biotechnology Industry," *Proceedings of the National Academy of Sciences, USA*, 93 (1996): 12709-16, especially 12714-16; Lynne Darby, Michael Zucker, and Jeff S. Armstrong, "Geographically localized knowledge: spillovers or markets?" *Economic Inquiry*, 36 (1) 1998: 65-86.