What Do Research Universities Do?
How Academic Discovery Creates Public Value.

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Chapter 1. Understanding Public Investments in Academic Research.

The United States' academic research enterprise is the most powerful engine for creating and sharing new knowledge in human history. Its ability to do both things is under threat. Tight federal budgets and competing priorities have increased political pressure on funders to invest in projects and topics that seem likely to yield clear, quick, and significant practical payoffs. The public value of research is important, but using economic returns to pick scientific winners suggests three fundamental misunderstandings. Policies that seek to maximize returns on public investments in discovery and training will damage the academic research enterprise because they are based on faulty beliefs about how academic research works, what universities actually produce, and how those products result in social and economic benefits.

In the wake of the Great Recession, politicians are increasing the pressure on funders and universities alike. Elected officials challenge the validity of particular grants, work to limit inquiry in fields they dislike, and seek, in the words of former Republican Congressman John Porter, to substitute "political judgment for scientific" evaluation.[1] In 2013, Representative Lamar Smith (R-TX), the chair of the House Science Committee, drafted legislation to require the National Science Foundation (NSF) to "certify that any pending research grant addresses national interests and problems of "utmost importance to society." That draft came just days after Congress approved an amendment that Senator Tom Coburn (R-OK) attached to the 2013 spending bill, which prohibited NSF funding of Political Science research unless the foundation's director certified that projects advanced national security or economic development.[2]

Soon thereafter Smith and then House Majority Leader Eric Cantor (R-VA) published an op-ed column in *USA Today* that cast longstanding tensions[3] between scientific autonomy and public obligation in stark relief: "[W]e all believe in academic freedom for scientists [but] federal research agencies have an obligation to explain to American tax payers" how their money is being used. I do not disagree. But, they continued, "[r]eprioritizing the government's research spending in favor of improving Americans' quality of life is not anti-science. It is common sense."[4] Treating funding for research projects like investments in stocks where clear measures of return can be assigned to particular bets introduces two pernicious misconceptions, which I call the fallacies of interdependence and direct impact, into discussions about the public value of academic work.

The fallacy of independence assumes that the products of different scientific fields are separable. The idea is that funders know what society's pressing problems are and that prioritizing projects that speak to those needs is relatively simple. As Senator Coburn said in a 2013 letter to the director of NSF: "While the scientific mind seeks to understand all aspects of the world around us, some research topics are simply more likely to contribute to truly meaningful discoveries or knowledge." The Senator goes on to highlight two such areas, suggesting that funds saved by limiting funding to projects with less potential be redirected to support "research to design a next generation robot limb to treat injured war heroes or a life saving hurricane detection system."[5] I do not believe that reaching agreement on priorities is an easy matter.[6] Even when there is a consensus, big problems often require solutions that span unexpected fields. Society's pressing challenges are usually too wicked for us to be certain about what kinds of tools we need in advance.[7]

Consider the challenge of national security after 9-11 when identifying and locating members of small, secretive groups became a pressing priority. The combination of social network theory and computational techniques from computer science has proven useful in that effort.[8] The possibility of applying network methods to pressing national problems today rests upon decades of academic work in several different fields,[9] most of which would be on the chopping block under a return on investment logic for prioritizing spending.

Little pioneering social network research would have met the "common sense" test of improving quality of life by addressing pressing societal problems. Consider just one example. In the early 1970s an anthropologist named Wayne Zachary used support from an NSF graduate fellowship to spend three years studying the social organization of a 34-person university karate club. In 1977 he published an influential paper that explained the group's dissolution into two competing organizations using network methods.[10] Zachary's data and findings became tools for later network research. Nearly 30 years later, a physicist named Mark Newman used the karate club to test a powerful algorithm for identifying small, cohesive groups in large networks.[11] The ability to identify what network scientists call "communities" in very large networks is useful to the project of finding potentially suspicious groups and individuals through passive observation. Likewise, techniques for understanding the dynamics of very large networks contribute to public health by improving understanding of disease transmission and to the economy by deepening capabilities for information transfer.

Newman also tested his algorithm on other datasets, but he notes that the karate club has become “something of a standard test of community detection algorithms.”[12] Newman’s NSF-supported research had clear relevance to problems of national interest when it was funded in 2004 and thus it seems likely that it would pass muster even with today’s skeptical congressmen.[13] Zachary’s work certainly would not. In retrospect it seems that it should, but the clarity of hindsight is deceptive.[14] I doubt that anyone could have accurately assessed the eventual scientific and practical contribution of the karate club project when Zachary’s fellowship was approved, some time during Nixon’s first term.

This small example is far from unique. When ideas, tools, and data move across fields of science, innovation often results. Such movements demonstrate the difficulty in determining the potential return on any given research investment when it is made. Interdependence among fields, methods, and topics makes the kinds of predictions necessary to prioritize high return science suspicious. Giving less support to projects that seem unlikely to yield returns today could easily deprive future investigators of techniques or ideas that might speed discovery of solutions to tomorrow’s pressing scientific or practical problems.

Prioritizing funding based on expectations of practical returns also succumbs to a second fallacy: the fallacy of direct impact. Analyzing costs and benefits makes it necessary to imagine that grants directly create social and economic returns. But they don't. Rather, research investments enable work that creates and sustains the capacity to produce discoveries and train people.

Discovery and training are both collaborative efforts involving many individuals. The social system that supports research is the proper target for investment. That system is the reason why important scientific and technical problems are often solved simultaneously by multiple individuals or teams.[15] The fact that "multiples" are commonplace suggests that our research enterprise is robust. It affords many opportunities for difficult problems to be addressed by different groups, often using distinct approaches, enabled by the particular scientific capabilities. In some cases, such as the discovery of induced pluripotent stem cells, different routes to the same result allowed researchers in the field to identify and develop more efficient and effective methods.[16] In other cases, such as the recent observation of the Higgs Boson by two separate experimental groups working at the Large Hadron Collider near Geneva, multiple discoveries provide the valuable service of replication and validation.[17]

Funders should not second-guess peer-review based estimations of scientific importance to support people or projects they believe will produce the best returns. Instead, they should try to sustain an enterprise that can identify and respond to compelling new questions and unexpected needs. Academic research funding helps develop human knowledge, but it also hedges against an uncertain future. Both needs are served by an organization that can respond effectively to unforeseen issues.[18] Emphasizing clear returns on individual investments is the wrong way to create such a system.

Individual grants generally cannot have social or economic impact. At best, they create conditions for people to be trained and discoveries to be made. New discoveries are often codified in publications, patents or other formats such as software and laboratory protocols. It is tempting to assume that grants result in findings that in turn create economic and social value, but codified knowledge alone is rarely enough to allow a discovery to be replicated or adapted in a new setting.[19] For instance, the network algorithm that I mentioned earlier may be valuable in national security or other applications. Presuming so, its impact would result neither from the grant that funded its discovery, nor from the publication that reported it. Instead the people whose skills and knowledge allowed them to identify, understand, and effectively implement it in response to a particular problem create public value. Because it is common for discoveries to lay fallow before their use becomes apparent, a large varied and accessible store of published knowledge is an essential product of science funding. But that pool of findings too is insufficient to generate economic and social returns.

So, innovation occurs as people learn new things, master new skills, and adapt both kinds of discoveries to new situations and needs. Such applications often require input from people who had a part in the initial discovery. At the frontiers of research, as Robert Oppenheimer famously noted, "The best way to send information is to wrap it up in a person."[20] Focusing on the people who do scientific work as a means to understand how research creates public value suggests the need to take seriously the overlapping social organization of discovery and training, as well as the movement of individuals from campuses to other workplaces. For all these reasons, the effects grants exert on economic and social problems are indirect, at best two or three steps removed from the initial investment.

"Common sense" efforts to prioritize projects with high social and economic returns are wrong because research fields are deeply interdependent and because federal funding indirectly creates social and economic returns. Grants enable scientific work. Scientific work spawns collaboration networks as people work together in teams that span projects and often organizations. Those networks underpin the social system that creates knowledge and skilled people. People's movements back and forth between the academy and other parts of society allow for the application of knowledge, which generates many of the benefits that are the promise of our federally funded research system. This process is centered at universities. We need a better toolkit for understanding and improving what they do.

Most federally funded fundamental research in the U.S. is conceptualized and conducted on university campuses.[21] In 2011, the U.S. government spent more than $209 for every man woman and child in the country to support academic projects.[22] Our society makes that investment to increase human knowledge and improve the lives of those who ultimately pay the bills. But as pressure mounts to justify research in immediate practical terms, it has become clear that too little is known about how scientific work generates economic and social returns to support wise decisions. Dangerous misconceptions thrive in the absence of rigorous, realistic analysis. As John Marburger, science advisor to President George W. Bush, said: ". . . the social science of science policy needs to grow up, and quickly, to provide a basis for understanding the enormously complex dynamic of today's global, technology-based society."[23]

Explaining the public value of academic research requires a new framework for thinking about the contemporary research university. This book uses sociological tools to analyze the collective dynamics of complex networks that link people on campus and connect universities to the larger economy.[24] I begin with the idea that research funds are investments in a complex, interdependent social system that produces knowledge. New discoveries are both codified and embodied in skilled people. The movement of knowledge between campuses and other settings is the engine that turns public funds into economic and social returns.

Research grants yield short-term economic returns because the funds let investigators hire people and buy things.[25] Yet the true value of fundamental research becomes clear only on a longer time scale as skills, techniques, and findings travel through multiple pathways from campus into the larger society. The discoveries that are made and the people that are trained with federal R&D funds thus shape technology, industry, and the economy while activity in those realms influences work on campus. This two-way flow of people and ideas allows investments in academe to contribute significantly to the health, wealth, and wellbeing of society. Understanding how this process occurs means shifting from a focus on what universities spend to an inquiry about what that spending lets them to do.

Let us both consider the text you are reading. The research that prepared me to write this book was supported by funds from 7 grants. The National Science Foundation awarded four of those to my institution across almost a decade. That money allowed me to hire some 40 undergraduate research assistants who generally worked with me for a semester or a summer. I also hired 10 doctoral students and post-docs whose work was longer and more intensive. Subcontracts and other arrangements supported work by six established collaborators on my campus and at four other organizations. We produced a substantial number of findings, papers, reports, presentations, dissertations, undergraduate theses, code, documentation and this book.

Other aspects of my research that are not germane to this book were supported by different grants, by institutional funds, or by no financial investments at all. The people who worked on those projects overlap, but only partially, with those who contributed to the studies that went into this project. All my faculty colleagues have other projects. Some of those are related to our joint work. Some are not. Regardless, the contributions my collaborators make to our research are informed by what they learn in other parts of their work, as are mine. My graduate students and post-doctoral fellows typically contribute to other projects. They also work to develop their own. Students too carry information, techniques, ideas and painfully won lessons about what doesn't work back and forth across groups and teams.

This book has my name on it and I alone stand behind its contents. In the strictest sense, though, it was produced in a complicated, far-reaching network of collaborators and students that spanned many grants and a number of years. The doctoral students made their own discoveries and went on to work in other places – including universities, technology firms, nonprofit organizations, and government agencies – on new topics with different people where (I hope) the skills and knowledge they learned on my team served them well. If you multiply my projects a few thousand times and expand them to include nearly every conceivable topic of research, the resulting web of relationships approximates the collaboration network at one large research university. If you imagine several hundred networks in all the organizations where academic research is done and allow them to take on different characteristics in each new location, you will gain a sense of the scale and complexity of the academic research enterprise. If you begin to ask how people and ideas move across campuses and back and forth between universities and other settings, you will glimpse the national and global innovation system of which academic research is a key component. Networks at all of these levels allow universities to produce, absorb and translate new knowledge. Those networks are the things public investments should be used to sustain.

Universities and Networks: Sources, Anchors, and Hubs

Universities are important in their own right, but they also contribute to our quality of life because they are *sources* of key inputs for the economy and society. Research universities use federal and other investments to support work that generates findings and people who know how to use them. The ability to do this varies from campus to campus and that variation is a due at least in part to differences in the structure, composition, and capabilities arrayed in distinctive collaboration networks.

Universities also play significant roles in larger inter-organizational networks. Their engagement with partners in many industries and sectors can be an important source of new problems and innovations that influence research. In the short term, universities contribute to society by serving as *anchors*[26] that add resilience and responsiveness to regional economies. In the longer term, universities create and sustain possibilities for innovation and growth because they are *hubs*[27] that span diverse industries, sectors, and locales. I examine the networks universities participate in and create as a means to explain what they do and how they do it. Answering the question posed by my title requires a deeper examination of what it means to say public research organizations are sources, anchors, and hubs.

Network Sources.

The first answer I offer to the question posed by my title treats universities and their collaboration networks as essential sources of new knowledge and skilled people. The most successful campus networks must consistently produce new things. They must also reproduce themselves over time while staying open and responsive to problems that arise elsewhere. Social systems that are conservative (in that reproduce themselves) and innovative (in that they produce novel things) are interesting, difficult to engineer, and fragile. Earlier I suggested that multiple discoveries indicate that a social system, rather than a brilliant individual or exceptional team, is responding to a scientific or technical problem. What, though, are the social conditions that we might expect to yield important multiple discoveries?

Let's begin at the turn of the 20th century when two great geniuses, Albert Einstein—then a struggling, obscure German physicist working in the Bern Patent Office—and Henri Poincare—then a celebrated French mathematician and philosopher who was also president of the Paris Bureau of Longitude—were both working to answer a fundamental question about the nature of time. They independently reached nearly identical conclusions, but Einstein's answer became a key part of the revolutionary theory of special relativity. Poincare's discovery was largely forgotten. Popular imagination and their own writings treat Einstein and Poincare as abstract geniuses whose conceptual work was based on thought experiments divorced from the concerns of everyday life.[28] But Peter Galison, a prominent historian of science, has painstakingly demonstrated that this idealistic view is incorrect.[29] Both men's similar discoveries and their different impact resulted from the complicated social, political and technical worlds each inhabited.

The practical challenge of synchronizing distant clocks was an important technical problem facing European society in the early years of the last century. Philosophical, political, scientific and economic forces aligned to make this problem at once an abstract concern of conventionalist philosophy and theoretical physics and an immensely pragmatic worry of engineers, navigators, and colonial powers bent on controlling far-flung empires. All these threads of concern aligned to produce what Galison calls a moment of "critical opalescence" where whatever abstract or practical question one wished to address pertaining to time led back to coordinated clocks. The threads of coordinated time converged in the patent office where Einstein evaluated new inventions, and the Bureau of Longitude, where Poincare struggled with methods to establish a ship's position at sea. The fact that these two brilliant men stood at such organizational "exchanges" made them " . . . witnesses, spokesmen, competitors, and coordinators of the cross-flows of coordinated time."[30]

The places where Einstein and Poincare worked, the problems they faced, and the people they interacted with made their multiple discovery possible. Their social positions also help explain why Einstein's solution to the problem of coordinated time revolutionized science while Poincare's did not. The two solutions were essentially identical except in one particular. Poincare, the established, elite scholar tried to preserve the day's scientific consensus by integrating the now discredited concept of the ether in his theory. Einstein, the newcomer bent on rethinking physics, jettisoned this legacy of 19th century mechanics with radical results.[31]

This retelling of coordinated time suggests hypotheses about the social conditions necessary for important multiple discoveries to occur. People with necessary skills and capacities must be present and working in settings where many different problems that span practical and conceptual concerns are active. At least some of those people must be willing and able to discard conventional wisdom in order to pursue answers to questions of concern. This means that failure is likely to be commonplace and should not be considered a disaster or a waste. It also suggests that established scholars must have the capacity to train and mentor newcomers whose work may challenge the status quo their advisors invested careers to build. Moreover it implies that the system as a whole should be insulated from larger social pressures to conform to conventional beliefs. Such insulation, however, should not come at the cost of separation from the concerns that animate contemporary social and economic life.

Radical discoveries like the theory of special relativity are exceptionally rare, but the conditions that gave rise to them should also enable less radical insights. Similar features characterize the contemporary research university. Imagining universities as organizational scaffolds for complex collaboration networks and focal points where flows of ideas, people, and problems come together offers a systematic way to assess the potential for innovation and novelty.

Unlike the story of Einstein and Poincare, most of today's cutting edge science is the province of teams.[32] Individual careers and the trajectories of fields are shaped by the structure and composition of research groups. One of the key activities of a contemporary Principal Investigator (PI) is to define an intellectual agenda and marshal the resources necessary to pursue it. On a day-to-day basis, science is a process fueled by increasingly cutthroat competitions for grants, which PIs must bundle to sustain a career long research trajectory.[33]

One result of that competition is collaboration networks. Those structures evolve on and across campuses, creating many possibilities for ideas and techniques to be combined in new ways. Innovation results from such "recombinations."[34] Historical accidents, organizational differences, the physical organization of campuses,[35] the strategic decisions of funders or administrators, and even personality conflicts among researchers can lead otherwise similar networks to evolve in distinct directions at different universities. These diverse network configurations create conditions that allow the academic research system to produce and integrate unexpected discoveries.

Six hundred and twenty-four U.S. campuses reported some federal R&D expenditures in 2012.[36] About 18% (110) of those universities did at least $100 million worth of publicly funded research. Those institutions account for about 83% of all federal research investments. They are located in 38 states and the District of Columbia. U.S. national capacities for research are defined by the structure, composition, and content of collaboration networks on these campuses. Those networks vary dramatically from campus to campus. As a result when a new problem is identified, the size and diversity of the system means multiple approaches to its solution will be the rule and multiple discoveries will be common. Public investments should be made with an eye toward sustaining the scale and diversity of the system rather than to identify the one efficient route to solving a known problem.

Understanding when campus collaboration networks are poised for creative innovation requires attention to the composition of the teams that actually do scientific work, to the structure of connections among people and teams, and to the scientific capabilities that are arrayed in those structures and teams. In the terms I develop above, the composition of scientific teams suggests the range of different intellectual and conceptual tools that can easily be brought to bear on a project and the possibility for risky approaches to research.

The structure of networks is important because the relationships among people on campus determine how easy it is for individuals to search for, find, and integrate necessary techniques and information into their work. Finally the content of projects pursued in these networks indexes the range of scientific capabilities available for researchers to access and combine as they work to innovate on campus.

Fertile sources of knowledge have three characteristics. First, their teams are diverse. They bring together people with different backgrounds and different levels of commitment to the established wisdom of their fields.[37] As sociologist Michele Lamont demonstrates in a recent study of interdisciplinary peer review, the different "evaluative cultures" that researchers bring to their evaluations of people, projects, and findings create conditions where few overarching pieces of conventional wisdom survive without challenge.[38]

Second, their networks are balanced. They manage to maintain both an open character that has been shown to help people generate good, novel ideas and pockets of tight, cohesive connections that enable the arduous work of turning those insights into discoveries.[39] Networks that afford people the chance to draw ideas and resources from disparate, otherwise loosely connected fields generate "aha" moments of insight necessary to innovation. At the same time the difficult and uncertain work of transforming such insights into validated discoveries requires the kind of trust and mutual accommodation most often found in cohesive networks where many people share overlapping ties.

Finally, their scientific capacities are complex. The knowledge and skills these networks combine encompass many different research capabilities. More importantly, those combinations are relatively rarely found together, can be repurposed and re-aligned in numerous ways to address new problems or discoveries and thus can both generate unexpected discoveries and respond to unexpected needs.[40] Networks are the wellspring of discovery but the things academic research produces are only the first step toward public value. It is also essential to examine how campuses are positioned in larger networks defined by flows of people and ideas between universities and other organizations.

Network Anchors

A second answer to the question I pose in this book's title has to do with the ways that universities act as citizens of their regions and the nation. In addition to contributing to society by generating knowledge, universities add to the robustness and resilience of regional and national economies by being *anchors.* What does it mean to say that organizations are anchors?

The metaphor has several related implications. In common sense terms an anchor holds a boat or other object in place. Being anchored yields a measure of stability, safety and even permanence in the face of unexpected, changeable or dangerous circumstances. It makes sense to think of universities in these terms for several reasons. First, they are more geographically fixed than many other types of organizations and, at least until recently, their reliance on public funding of various sorts made them less prone bankruptcy than other types of organizations. There are lots of things one could say about my institution, the University of Michigan, but two stand out in this regard. The first is that it is very unlikely to go out of business. The second is that it is unlikely to move to Tennessee or Alabama. Equivalently large businesses and regionally important businesses routinely change locations or die.

The stability and fixity of universities helps explain why much of their activity generates local economic benefits. Even though federally funded research represents a relatively small portion of employment and spending by most campuses, it is important and instructive. When a new grant is awarded to an institution, the investigators whose project it funds tool up by hiring people and buying necessary supplies and services. In a recent paper, my colleagues and I examined the characteristics of the workforce and vender purchases supported by federal grants made to 8 campuses that are members of the Committee for Institutional Cooperation.[41] We found that these grants paid wages to some 50,000 people in fiscal 2012. Nearly three quarters of those individuals were students, post-doctoral fellows or staff. Such hiring adds to the economy of regions that are home to universities because good jobs allow people to spend their earnings in local housing markets, restaurants, and shops.

We also tracked nearly $1 Billion in vendor spending. Nearly one third of that money was spent within the state or the county where a university was located. In the simplest terms, universities are anchors because they can usually be counted upon to stay in one place and to consistently hire people and pursue activities – such as research, teaching, and health care – that contribute directly and indirectly to that place. This is not a unique characteristic of universities, so care must be taken to establish appropriate comparisons. It is also important to note that these near term economic benefits are a happy byproduct of core university missions, not their purpose or justification.

There are two other more specialized ways to think about university anchors. The first is adapted from studies of retail marketing, which call the large department stores typically found at the ends of shopping malls "anchor tenants."[42] The big stores in malls are important because they draw shoppers to the mall and thus help create demand for products sold by smaller stores. But this means that anchor tenants also help define what kinds of specialized stores can thrive. Think about the differences between malls that are anchored by luxury department stores such as Saks Fifth Avenue and those that are anchored by less expensive brands such as Sears.

Universities too are anchor tenants because they draw people (students, faculty, staff) to them. Research institutions also attract other organizations that seek to serve demand created by their people or to access the products of their work. College towns are famous for many things, one of which is coffee. There are an immense number of specialty coffee shops within a short walk of my campus. Those venues exist to serve demand created by the faculty and students of the university. To a casual eye, their density declines as distance from the campus increases. It is a simple thing to note, but universities serve as anchors by attracting people who expand local markets for some types of goods and services more than others in the same way that some department stores increase traffic to high-end jewelers and others expand demand for discount shoes.

A more pointed example comes from the human therapeutic and diagnostic biotechnology industry, a high tech sector where universities and academic research have played a particularly decisive role.[43] That industry is very geographically concentrated with large and vibrant clusters of firms arising in and around Boston, San Diego, and the San Francisco Bay Area. Universities and other public research organizations play a very important anchor tenant role in all three places, as companies want to be near academic labs in order to benefit both from the new discoveries and talent they produce.[44] Twenty years ago large multi-national pharmaceutical firms maintained no presence in these locations. Today the largest of them have established research facilities there. The world's second largest drug company, Novartis, has located its research headquarters mere blocks from MIT and minutes away from Harvard, Boston University and the impressive array of universities, colleges, teaching hospitals and research institutes in the greater Boston Area. The company built another facility in San Diego on a relatively small lot adjacent to the Scripps Institute and near the Salk Institute and the campus of UC San Diego. In both cases, world-class research and training in the life sciences helped to draw potential partners to a region.

Universities can help add to the economic wellbeing of their regions and their presence can help to define the character of a place by drawing both people and organizations to locate there. Universities also serve as anchors for the networks of inter-organizational relationships that characterize robust industrial districts.[45] When universities like UC San Diego or MIT collaborate with corporations in their regions to develop and share information they can play a distinctive matchmaking role because they do not directly compete with or seek to control the activities of their partners. As sociologist Walter Powell and colleagues put it in a study of the emergence of biotechnology clusters in the United States: "We think of an anchor . . . as a well-connected organization . . . which mobilizes others and fosters collective growth."[46] The most abstract sense of what it means for universities to be anchors, focuses on how they occupy their positions in markets and networks. But what are those positions?

Network Hubs

The third answer to the question I pose in the title has to do with the unique positions universities occupy in the structure of national and global innovation systems. Universities create and sustain possibilities for growth and for responses to unexpected challenges or opportunities because they are *hubs*. A hub is a common passage point and a focus of attention because it the central connector of a system. Think about airports. Hubs like Chicago's O'Hare have lots of flights on lots of carriers to lots of places. They are one hop from almost any destination in the world. Many people go to Chicago, but vast numbers of travellers pass through O'Hare on the way to somewhere else. In the global network of airports, hubs shorten the distance between any random pair of cities. Layovers notwithstanding, hubs are shortcuts. When they fail or close, the system grinds to a halt.

University campuses are hubs in a few of these senses. They are passage points for many people. This is obvious to professors, who face the same lecture halls filled with fresh new faces each year and who enjoy homecoming for the chance to hear where past students have taken themselves. Universities are also hubs in the sense that they are, metaphorically, one step from everywhere. As sociologists Mitchell Stevens, Elizabeth Armstrong, and Richard Arum put it: " . . . higher education is a hub connecting some of the most prominent institutional sectors of modern societies" and as such universities are " . . . sites where institutions intersect."[47] We would not be surprised to see travellers from many nations or to hear many languages spoken in the world's airport hubs. In much the same way, university campuses are places where it is not surprising to come across politicians, business people, sports stars, humanitarians, scientists, entertainers, physicians, artists, diplomats, actors, military officers, entrepreneurs, musicians, journalists, lawyers . . . The list could go on, but the point is an important one. A large university with a diverse portfolio of research and teaching is a shortcut between many parts of society and the economy. Like airline hubs, if campuses close themselves off, knowledge and people have a harder time travelling where they need to go.

The movement of people and ideas from campus to other settings creates network connections that shorten the distance between different industries and sectors. For that reason campuses have a unique capability to be organizational "exchanges" where multiple "threads of concern" converge in the way that Galison described Einstein's patent office and Poincare's bureau.

An entire university campus is too large and diverse to provide an easy illustration of this idea, but consider one small part of a campus as a stand in for the whole. Andrew Nelson, a business professor and musician, has spent the last fifteen years studying a research institute affiliated with the Stanford University Department of Music whose work nicely illustrates this concept. The Center for Computer Research on Music and Acoustics (CCRMA – pronounced "karma") brings together people from fields as diverse as music, computer science, drama, engineering, art, physics and psychology to use computers in music performance and research on sound.

CCRMA is a study in contrasts. It is oriented toward avant-garde performances of electronic music and open source approaches to scholarship and research, but it is also the source of one of Stanford's most valuable portfolios of patents.[48] CCRMA's faculty and staff interact with non-profit organizations, large and small companies, user communities, and researchers in many different fields. Their connections allow them to quite successfully be a bit of all things to all people. In a telling example, Nelson cites a project on digital signal processing that was funded as a performance by the National Endowment for the Arts, as an advance in fundamental science by the National Science Foundation, and as new sonar application by the U.S. Navy. This "multivocality" is a source of CCRMA's success and a reflection of its hub-ness.[49]

Many, many threads of concern can come together on university campuses. When those campuses act as anchors and maintain the kinds of diverse, balanced and complex networks that can make them essential sources of new knowledge, they become utterly unique hubs in the global innovation system. Universities are typically stable institutions, after all the University of Bologna was founded in 1088 and several U.S. Universities are older than our nation. Regardless, the collaborative networks and research capabilities federal investments have helped to create on campus since the end of World War II are fragile and difficult to engineer. As a result, the ability of universities to serve as hubs fundamentally depends on their ability to be fertile sources. The productivity, the stability, and the reach of universities is the basis of their public value. Andrew Nelson's appraisal of the sources of CCRMA's success holds true for universities as well: " . . . the success of an individual or group engaged in this system may depend, in fact, upon this diversity of perspectives, participants, and goals."[50]

When collaboration networks are sustained by stable and broadly distributed research investments, when universities mobilize partners for the collective good and enable a free flow of people and ideas though campus, and when the connections those movements create bridge disparate pieces of the economy and society, the result is a robust but flexible innovation system. These features of universities are created and sustained by public investment and allow them to link domains of knowledge, economic sectors, markets and different types of organizations. The configuration and reconfiguration of these social and inter-organizational networks drives both the outcomes and the impact of research and training.

Thus, we must map the networks among people and organizations in order to begin explaining what universities, and, by extension, public R&D investments, do. Anything less treats science funding as slot machine with innumerable combinations and few rules for identifying winners. If we do not systematically examine the workings and structures of university R&D, we are gambling on very uncertain outcomes.

Consider a familiar example that illustrates many of the ways universities and their networks help to turn grants into knowledge into social and economic returns.

Google and Page Rank

While writing this in my local library, I rely heavily on a search engine, Google, to locate references, check facts, and procrastinate. The corporation whose website I visit, Google, Inc., is currently valued at nearly $400 Billion. It employs 48,000 people and completes about 12.7 Billion searches per month from U.S. users alone. In addition to bringing me these facts, "Google" has entered the English lexicon as a verb. My elementary school children sagely suggest "googling" questions I can't readily answer. Yet less than 20 years ago the search engine, the corporation, and the verb did not exist.[51] It is not a cure for cancer or Alzheimer's disease, but Google is a spectacularly successful company that has driven economic growth, created jobs, and (mostly) improved the quality of life of the people who use it. Google is just the sort of outcome that those concerned with the economic returns to science funding most hope to replicate.

So, where did Google come from? More importantly, if we wanted to "re-prioritize" federal research spending in order to generate more Googles, what should we do? The answer, I believe, is not that we must pick particular winners to gamble on. Instead, we should ask how we can cultivate a robust and responsive system that is poised to yield discoveries and outcomes we can at best dimly envision or cannot see at all when we place our bets.

The story is well known. As Google's investor relations page explains ". . . our founders, Larry Page and Sergey Brin, working out of a Stanford University dorm room, developed a new approach to online search that quickly spread to information seekers around the globe."[52] Like many other visible technology companies, Google emerged from entrepreneurial efforts that began on the campus of Stanford University.

A 2004 National Science Foundation webpage[53] explains that Google's core technology, an algorithm called PageRank, was developed and implemented under a grant to two computer science professors at Stanford. Those researchers were Hector Garcia-Molina and Terry Winograd who was Larry Page's advisor. Funding from that grant spanned five years (1994-1999) and totaled more than $4.5M. The project it supported, named the "Stanford Integrated Digital Library Initiative (DLI)" sought to "to develop the enabling technologies for a single, integrated and "universal" library, proving uniform access to the large number of emerging networked information sources and collections." As the project progressed, researchers recognized that an important "emerging networked information source" was the World Wide Web.

The DLI employed Larry Page as a graduate assistant and also involved Sergey Brin, who was supported by an NSF Graduate Research Fellowship.[54] In 1995 Page and Brin began to work on PageRank. Stanford University filed a provisional patentin 1997.[55] Page and Brin presented a conference paper in 1998.[56] The utility patent that was filed a year later in 1998 and that was issued in 2001 acknowledged government support in the form of the NSF grant to Molina and Winograd. Under the terms of the 1980 Bayh-Dole act, that patent, which listed Larry Page as the sole inventor, was owned by Stanford University. Google was incorporated in 1999 with initial funding from an angel investor named Andy Bechtolsheim, a Stanford Electrical Engineering Ph.D. and founder of Sun Microsystems. Initial investments from two high profile Silicon Valley venture capital firms (Kleiner, Perkins, Caufield & Byers and Sequoia Capital), both of which also have strong ties to Stanford) soon followed. Stanford signed an exclusive license granting sole right to use the PageRank algorithm to Google in 2001, a deal that was renegotiated to expand the term of exclusivity in 2003. In 2004, as Google approached its initial public offering (IPO) the prospectus it filed with the Securities and Exchange Commission (SEC) revealed that six of its 14 officers and directors had affiliations with Stanford. The most prominent Stanford affiliated board member was John Hennessey, the University's President and a very successful entrepreneur in his own right.

Even this very truncated and simplified story suggests that a complex web of relationships created by movements of ideas and people underpins both the invention of Page Rank and its translation into a successful publicly traded company. But if we want to really understand how public investments catalyzed those developments, three questions need to be answered.

First, what did it take for Page and Brin to develop PageRank? Second what enabled that clearly very good idea to become the core of an exceptionally successful company? Most importantly, what role did federal funding play?

The idea that funding the Stanford Digital Libraries project resulted directly in Page Rank is appealing, but there is something missing in that view. Assuming direct impact of the DLI grant resembles a familiar *New Yorker* cartoon where two scientists stand at a black board pondering chalked equations bracketing the phrase "and then a miracle happened." It is unlikely that even Larry Page could accurately and completely re-create the steps that led to his discovery.[57] Published descriptions of PageRank's invention highlight the dense web of talented and often entrepreneurial scientists that characterized the Stanford campus in the mid to late 1990s.[58] Both relationships with collaborators and advisors and the social capacity encoded in Stanford's larger collaboration network are essential to understand how a doctoral student's plan to archive the web transformed into a search algorithm that could be the basis of a firm with a $400 Billion stock market valuation.

Here too there are multiple discoveries. PageRank was one of three roughly contemporaneous inventions that used the link structure of the web as the basis for search. Another search algorithm, RankDex, was developed by Robin Li, then an engineer working at a subsidiary of the Dow Jones Company. RankDex later became the basis of Chinese search firm Baidu. That company now has a market capitalization of more than $200 Billion and is Google's primary global competitor. A third approach, Hypertext-Induced Topic Search (HITS), was developed by Jon Kleinberg, a Cornell computer science professor who was working as a visiting researcher at an IBM research lab. All three inventions were patented.[59] Two of the three algorithms supported the founding of a successful, publicly traded firm. In both those cases the inventors were founders of the company.

Stanford was not a unique source of relevant discoveries, but something about the environment created through its various relationships with individuals and organizations in Silicon Valley was key to Google's early success. The special sauce of vibrant regional technology clusters is hotly debated, but most commentators agree that some mix of social network ties among individuals and strategic relationships linking organizations is essential. The important role universities play in forging and sustaining both kinds of networks is just beginning to be understood.[60]

Stanford's PageRank patent and the licensing deal with Google is also an important part of the story. But the majority of academic patents (and indeed patents generally) are not lucrative.[61] And, in fact, a similar patented technology, HITS, did not result in a successful corporation. Only a few venture funded technology companies achieve the kind of spectacular success that Google has enjoyed.[62] The 1998 conference paper and the patent were the only published descriptions of the algorithm authored by Page and Brin, who left Stanford to found Google only after efforts to sell their technology to existing search firms failed.[63] Apparently the economic value of PageRank was not clear enough to entice established players to invest in it. Page and Brin's departure from Stanford is the primary form of technology transfer that enabled the company's success.

It is tempting to draw simple lessons from the Google case. Favor projects that address key concerns for recognizable emerging technologies. Fund research conducted by established faculty on elite campuses. Emphasize grants with clear potential for short-term economic returns. Encourage and reward entrepreneurship. Aggressively patent findings and license them exclusively to start-ups. Encourage talented students to leave the academy to pursue entrepreneurial dreams. I fear that these are the kinds of guidelines an overly simple, "common sense," effort to guide federal research investments toward national priorities might adopt.

Treating a complex and interdependent social process that occurs across relatively long time scales as if it had certain needs, short time frames, and clear returns is not just wrong, it's destructive. The kinds of simple rules I suggest above represent what organizational theorist James March called "superstitious learning."[64] They are akin to making the argument that because many successful Silicon Valley firms are founded in garages, economic growth is a simple matter of building more garages to house startups.[65] Understanding how universities work as sources, anchors, and hubs suggests an almost diametrically opposed set of rules for putting public resources into academic research.

Consider the idea that we should prioritize projects with clear applications to emerging technologies. That thought underpins much of the political debate about how to address national interests in research funding. Whether we are talking about nanotechnology or neuroscience, many funding programs target specific problems that appear ripe for social and economic impact. The Google case may seem to be exhibit A in this regard. After all, even the NSF draws a direct line from the Digital Library Project to PageRank and Google.

But while it is easy to see that the World Wide Web was important and growing in retrospect, the Stanford DLI proposal did not mention it. In an interview with Steven Levy, one of the PIs, Hector Garcia-Molina, noted that "The theme of that project was interoperability" and went on to suggest that the interests of graduate students such as Page and Brin drove the project toward questions pertaining to the emerging World Wide Web.[66] Clearly the challenge of identifying projects with direct relevance to emerging technologies is more complicated than the standard story of PageRank suggests.

The defining role played by graduate students demonstrates how connections among people who might never appear on lists of principal investigators or authors are essential. Indeed, one such student, Scott Hassan, who was also a graduate assistant on the DLI project but not an author on the PageRank paper or an inventor on the PageRank patent, played an important role in implementing the algorithm.[67] An important, but relatively little understood role of federal funding on campus is to bring together talent while allowing relatively young scholars room define their own projects.

Because they are also, explicitly, sites for training, university research teams can enable students to pursue approaches and topics that challenge or amend the status quo. Clearly the quality of faculty investigators and of the institutions where they work bears upon the horsepower and ambition of students, but focusing solely on established scientists and their campuses misses the point that discoveries depend upon and use information drawn from local sources and from more distant locations.

The relatively short time from the DLI grant's funding (1994) to Google's incorporation (1999) and IPO (2004), might also be taken to support an effort to prioritize projects that promise relatively quick returns.[68] But consider a broader view of the knowledge that Page drew together in conceptualizing his algorithm. If we examine the PageRank patent closely paying particular attention to what intellectual property geeks call prior art, we see that the DLI project was far from alone among federally funded contributions to the origins of PageRank.[69]

The PageRank patent application[70] cited 16 academic papers and one prior patent. The latter was assigned to Carnegie Mellon University, which also had a prominent computer science department. The papers that Page apparently relied on report work by 27 authors affiliated with 19 different organizations. Reading the acknowledgments of those papers reveals that this work was supported by 15 grants or contracts from NSF, NIH, the Office of Naval Research, the National Library of Medicine, two foundations and two corporations.

If we include the DLI grant and an NSF contract to a bibliometric start-up firm, a plurality (six) of those investments came from NSF. They represent an interesting mix of disciplines spanning the social sciences, computer science, citation analysis, and computational field theory. The earliest grant was an $81,000 NSF award made to a sociology professor at SUNY Stony Brook for "Mathematical Analysis of Corporate Networks" in 1974. The 1974 grant was acknowledged in a 1986 paper whose lead author had worked on the project as a graduate student. The 1986 paper, which presented a new disaggregated measure of prominence in a social network, was cited in the 1998 PageRank patent application.

In light of these connections, understanding the NSF's contributions to Google requires that we mentally add an additional 20 years to the five-year lag between the DLI grant and Google's incorporation. The first NSF grant we can very easily identify that plausibly helped to enable Page's discovery was made around the time he was born, on the other side of country, in a discipline far removed from computer science, at a time when the possible applications of mathematical network theory to the link structure of a massive online corpus of websites would have seemed like science fiction.

Moreover, the 1974 grant was to study the interlocking board of director memberships of large US corporations, a topic of interest to social scientists but one that not even the most prescient policy maker might associate with dramatic economic returns. Between 1970 and 1997, the National Science Foundation made tens of thousands of research investments totaling more than $52 billion dollars.[71] Of those, six grants and contracts[72] (for $10.5 million, 0.02% of the total) were awarded to investigators across two decades, four campuses, and multiple disciplines. They represent one very small needle in the haystack of the NSF's portfolio. Together those grants helped support the training of students and the discoveries that were important to the development of PageRank and, by extension, to the success of Google.

Explaining how such public investments in research and training result in public value requires that we broaden our view beyond returns on investment to single grants, lone geniuses, flashes of inspiration, patents, publications, and the entrepreneurial culture of single campuses to focus on bodies of knowledge, complex networks, and the movements of people and ideas back and forth between universities and the larger environment.

That shift requires us to simultaneously consider three things. First we must examine the strategic actions of people and teams who work to accomplish difficult goals under challenging, highly competitive conditions. Second, we must attend to the content and structure of campus wide collaboration networks that are the social matrix for discovery and training. Third, we must characterize the distinctive positions universities occupy in national and global inter-organizational networks created as ideas and people move back and forth between campuses and the larger economy and society.

These levels of analysis are nested. But action at micro, meso, and macro scales is not independent. A university's position in inter-organizational networks alters the capacities it can array in collaboration networks. Those capacities shape possibilities for action on the part of researchers and teams. At the same time, the successes and failures of individuals and teams can alter collaboration networks, rendering future discoveries more or less likely and eventually repositioning universities in the broader inter-organizational networks.

Many locations might have allowed smart computer scientists to develop technologies similar to PageRank. A faculty member from Cornell invented HITS while on leave at IBM. RankDex was invented by a corporate engineer. Universities are not the sole sources of good ideas. But they are the primary performers of publicly supported fundamental research and many good ideas come from that work.

Good ideas alone are insufficient to yield economic returns. Stanford's position in the network of Silicon Valley was necessary to turn PageRank into Google. Google's success no doubt redounds to reinforce Stanford's centrality in the valley, to attract a new generation of smart graduate students, and to more or less subtly reconfigure collaboration networks around engineering and computer science.

I treat each level of analysis separately in the sections that follow. In the concluding chapter, I bring them together to argue that the key to understanding the public value of academic research is realizing that sometimes public investments help university campuses become the very rare and special social settings where activities taking place in multiple social registers align to make truly radical discoveries and their valuable applications possible. In the terms used by sociologist Walter Powell and his collaborators John Padgett[73] and Victoria Johnson[74] federal research funding helps universities to become sites where the entire innovation system is poised to both generate and integrate new discoveries and ideas. As Johnson and Powell put it "Poisedness thus refers to circumstances that are rich with potential, in which relations and trends at one level are available to be coupled with innovations at a different one."[75] That view puts universities and their networks front and center and requires that we examine how public investments create and sustain their capacity to be sources, anchors and hubs for our economy and society.

[1] Porter, John. "Remarks Upon Receiving The National Academy Of Sciences Public Welfare Medal, Its Highest Award." April 27, 2014

[2] Mervis, Jeffrey. 2013. "Proposed change in Awarding Grants at NSF Spurs Partisan Sniping." *Science.* 340:670.

[3] See, for instance, Guston, David and Kenneth Keniston (eds.) 1994. *The Fragile Contract: University Science and the Federal Government.* Cambridge, MA: MIT Press.

[4] Cantor, Eric & Lamar Smith. 2013. "Rethinking science funding." *USA Today.* September 30, 2013.

[5] http://www.coburn.senate.gov/public//index.cfm?a=Files.Serve&File_id=60c99a67-2f0d-4c83-9b3d-1d65225d6abb accessed 10/09/2014.

[6] And as Senator Coburn himself might say about questions that seem to have obvious answers, we're already pretty good at detecting hurricanes.

[7] Rittel, Horst W. J. & Melvin M. Webber. 1973. "Dilemmas in a General Theory of Planning." *Policy Studies.* 4: 155-169

[8] Carley, Kathleen, Jeffrey Reminga, & Natasha Kamneva. 1998. "Destabilizing terrorist networks."

[9] Freeman, Linton C. 2004. *The Development of Social Network Analysis: A Study in the Sociology of Science.* Vancouver: Empirical Press.

[10] Zachary, Wayne. 1977. "An Information Flow Model for Conflict and Fission in Small Groups." *Journal of Anthropological Research.* 33(4): 425-473.

[11] Newman, Mark E. J. 2006. "Modularity and Community Structure in Networks." *Proceedings of the National Academy of Sciences.* 103:8577-8582.

[12] Ibid. pp 8579

[13] The former was an award (DMS-0405348 "Structure and Dynamics of Social Networks and Other Networked Systems") made in 2004 for $286,421 at that time it would likely have been clear that such fundamental research could have implications for national security, but the abstract of the award (accessed http://www.nsf.gov/awardsearch/showAward?AWD_ID=0405348&HistoricalAwards=false on 10/01/2014) cites its potential value for understanding the spread of information through society as well as the transmission of physical diseases or computer viruses.

[14] Weick, Karl. 1995. *Sensemaking in Organizations.* New York. Sage.

March, James G. 2011. *The Ambiguities of Experience.* Cornell University Press.

[15] Merton, Robert K. 1961. "Multiples in Scientific Discovery: A chapter in the sociology of science." *Proceedings of the American Philosophical Society.* 105:470-486.

[16] In 2007, two research teams headquartered in Madison, Wisconsin and Kyoto, Japan, separately demonstrated methods to "reprogram" adult human cells called Fibroblasts into a pluripotent state that allowed them to subsequently develop into any type of human tissue. The groups used similar but slightly different methods to accomplish this feat relying on different means to introduce somewhat different sets of genes into adult donor cells. Yu et al. 2007. "Induced Pluripotent Stem Cell Lines Derived From Human Somatic Cells." *Science.* 318: 1917-1920. Takahashi et al. 2007. "Induction of Pluripotent Stem Cells from Adult Fibroblasts by Defined Factors." *Cell.* 131: 861-872.

[17] The ATLAS and CMS experiments at CERN both reported findings consistent with the Higgs, but where the CMS result fell just short of the standard level of statistical significance required in the field of higher energy physics, the ATLAS result surpassed that standard. Cho, Adrian. 2012. "Higgs Boson Makes It's Debut After Decades Long Search." *Science.* 337: 141-143.

[18] Chandra Mukerji makes a similar point in her 1990 book, *A Fragile Power: Scientists and the State,* where she argues that federal science funding creates and sustains a reserve force of highly skilled and credentialed experts who can be called upon to legitimate government programs and policies. Though I do not pursue the political argument here, the larger point that federal funding creates substantial pools of scientific human and social capital that can be used to address numerous social and scientific problems is a good one.

[19] Collins, Harry. 2010. *Tacit and Explicit Knowledge.* Chicago: University of Chicago Press.

[20] Bird, Kai & Martin J. Sherwin. 2007. *American Prometheus: The Triumph and Tragedy of J. Robert Oppenheimer.* New York: Knopf Doubleday Publishing Group. P. 367.

[21] National Science Board. 2014. *Science and Engineering Indicators.* Arlington VA: National Science Foundation (NSB 14-01).

[22] The total figure of more than $65 Million is drawn from the Higher Education Research Expenditures Survey.

[23] John Marburger III. Speech to the AAAS Forum on Science and Technology Policy, 21 April 2005.

[24] Powell, Walter W. Jason Owen-Smith & Laurel Smith-Doerr. 2011. "Sociology and the Science of Science Policy." Pp 56-84 in Julia Lane et al (Eds.) *The Science of Science Policy: A Handbook.* Stanford University Press.

[25] This is true of all "stimulus" spending and not distinctive for research, though the kinds of economic effects research hiring and spending produce may be different than other types. I address this question in Chapter 4. Weinberg et al 2014

[26] Powell, Walter W. Kelly Packalen, & Kjersten Whittington. 2012. "Organizational and Institutional Genesis: The Emergence of High-Tech Clusters in the Life Sciences." Pp. 434-465 in J. Padgett & WW Powell (Eds). *The Emergence of Organizations and Markets.* Princeton University Press.

[27] Stevens, Mitchell L., Elizabeth A. Armstrong & Richard Arum. 2008. "Sieve, Temple, Incubator, Hub: Empirical and Theoretical Advances in the Sociology of Higher Education." *Annual Review of Sociology.* 34: 127-151.

[28] Barthes, Roland. 1972. "The Brain of Einstein." Pp 68-71 in *Mythologies.* New York: Hill & Wang.

[29] Galison, Peter. 2004. *Eistein's Clocks and Poincare's Maps.* New York: W.W. Norton & Company.

[30] Ibid. 41

[31] Dyson, Freeman. 2003. "Clockwork Science." *New York Review of Books.* November 6, 2003.

[32] Wuchty, S, BF Jones, & B Uzzi. 2007. "The increasing dominance of teams in the production of knowledge." *Science.* 316: 1036-1039.

[33] Owen-Smith, J. 2001. "Managing Laboratory Work Through Skepticism: Processes of Evaluation and Control." *American Sociological Review.* 66(3):427-452.

[34] Schumpeter, Joseph. 1939. *Capitalism, Socialism, and Democracy.*

[35] Kabo, Felichism, Natalie Cotton-Nessler, Yongha Hwang, Margaret Levenstein, & Jason Owen-Smith. 2014. "Proximity Effects on the Dynamics and Outcomes of Scientific Collaboration." *Research Policy.* 43: 146-1485.

[36] Figures are calculated from the NSF's Higher Education Research and Development survey accessed via the WebCaspar system (https://ncsesdata.nsf.gov/webcaspar/).

[37] Page, Scott E. 2008. *The Difference: How the power of diversity creates better groups, firms, schools and societies.* Princeton University Press.

Stark, David. 2009. *The Sense of Dissonance: Accounts of Worth in Economic Life.* New York: Princeton University Press.

[38] Lamont, Michele. 2009. *How Professors Think: Inside the Curious World of Academic Judgement.* Cambridge, MA: Harvard University Press.

[39] Burt, Ronald S. 2004. "Structural Holes and Good Ideas." *American Journal of Sociology.* 110: 349-399.

[40] Hidalgo, Cesar & Ricardo Hausman. 2009. "The building blocks of economic complexity." *Proceedings of the National Academy of Sciences.* 106: 10570-10575.

[41] The CIC includes members of the Big Ten athletic conference and the University of Chicago.

[42] Agarwal, Ajay & Iain Cockburn. 2003. "The Anchor Tenant Hypothesis: Exploring the Role of Large, Local, R&D Intensive Firms in Regional Economies." *International Journal of Industrial Organization.* 21: 1227-1253.

[43] Powell, Walter W. & Jason Owen-Smith. 1998. "Universities and the Market for Intellectual Property in the Life Sciences." *Journal of Policy Analysis and Management.* 17: 253-277.

[44] Zucker, Lynne, Michael Darby, Marilynn Brewer. 1998. "Intellectual Capital and the Birth of U.S. Biotechnology Enterprises." *American Economic Review.* 88: 290-306.

[45] Owen-Smith, Jason & Walter W. Powell. 2004. "Knowledge Networks as Channels and Conduits: The Effects of Spillovers in the Boston Biotechnology Community." *Organization Science.* 15:5-21.

[46] Powell, Packalen & Whittington *Op cit.* 439.

[47] Stevens, Mitchell. Elizabeth A. Armstrong & Richard Arum. 2008. "Sieve, Incubator, Temple, Hub: Empirical and Theoretical Advances in the Sociology of Higher Education." *Annual Review of Sociology.* 34: 127-151. Pp. 135.

[48] Nelson, Andrew. 2005. "Cacophony or Harmony? Multivocal Logics and Technology Licensing by the Stanford University Department of Music.*" Industrial and Corporate Change.* 14: 93-118.

[49] Padgett, John & Christopher Ansell. 1993. "Robust Action and the Rise of the Medici, 1400-1434." *American Journal of Sociology.* 98: 1259-1319.

[50] Nelson, Andrew. 2014. *The Sound of Innovation: Stanford and the Computer Music Revolution.* MIT Press. Pp. 12.

[51] In the interests of accuracy the verb "google" did exist but apparently pertained to a particular breaking bowl in cricket. Thank you, Google.

[52] https://investor.google.com/corporate/faq.html accessed 7/31/2014.

[53] http://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=100660 accessed 7/31/2014

[54] http://www.nsfgrfp.org/why_apply/fellow_profiles/sergey_brin accessed 7/31/2014

[55] U.S. provisional patent application Ser. No. 60/035,205 filed Jan. 10, 1997

[56] Brin, S. and Page, L. (1998) *The Anatomy of a Large-Scale Hypertextual Web Search Engine.* In: Seventh International World-Wide Web Conference (WWW 1998), April 14-18, 1998, Brisbane, Australia.

[57] On the challenges posed by scientific "memory practices" see Bowker, Geoffrey. 2006. *Memory Practices in the Sciences.* MIT Press.

[58] Levy, Stephen. 2011. *In the Plex: How Google works, thinks, and shapes our lives."* Simon & Schuster.

Stross, Randall. 2008. *Planet Google: One Company's Audacious Plan to Organize Everything We Know.* Free Press.

[59] RankDex is US Patent 5920859. HITS is US Patent 6112202.

[60] Saxenian, Annalee. 1996. *Regional Advantage.* Harvard University Press.

Lampe, David. 1988. *The Massachusetts Miracle: High Technology and Economic Revitalization.* The MIT Press.

Kenney, Martin & David Mowery (Eds.) 2014. *Public Universities and Regional Growth.* University of California Press.

[61] Wright, BA. et al. 2014. "Technology Transfer: Industry Funded Academic Inventions Boost Innovation." *Nature* 507: 297-300.

Mowery, David C. et al. 2004. *The Ivory Tower and Industrial Innovation.* Stanford University Press.

Jaffe, Adam & Josh Lerner. 2011. *Innovation and its Discontents: How Our Broken Patent System is Endangering Innovation and Progress, and What to Do About It.* Princeton University Press.

[62] Ritter, Jay. 1991. "The Long Run Performance of Initial Public Offerings." *Journal of Finance.* 46(1): 3-27.

Gompers, Paul and Josh Lerner. 2006. *The Venture Capital Cycle.* MIT Press.

[63] Levy pp . . .

[64] Levitt, Barbara & James March. 1988. "Organizational Learning." *Annual Review of Sociology.* 14:319-340.

[65] I first heard this analogy drawn by Luigi Orsenigo, an economist working at the University of Bocconi, Italy.

[66] Levy, Steven. 2011. *In The Plex.* New York: Simon & Schuster. P. 16

[67] Ibid. 17

[68] Though it is important to note that the five years that elapsed between the grant being funded and Google's incorporation spans more than two congressional election cycles. In today's political environment it might better to envision that time as spanning five federal budget battles. Computer science is also a 'fast' discipline relative to other areas, such as the life sciences, where valuable technologies may emerge from early stage research.

[69] By law, inventors on patents are required to disclose the relevant prior art for their inventions. During the patent examination process these sources are checked and where necessary others are added by staff people in the United States Patent and Trademark Office. The patent system is designed to trade exclusive rights to an invention for a limited time (currently 20 years) for full disclosure of the invention to the public (so that others can draw upon and use it). Thus, it is possible to examine the application for a patent that Stanford filed on behalf of Larry Page in order to see what pieces of prior knowledge he cited at the time of application.

[70] That patent is US Patent 6285999, the relevant application is US 09/004,827. The prior art references I discuss here were extracted from what is known as the "file wrapper," a compilation of all documents and correspondence pertaining to a patent. That file is available from the US Patent office and contains the original application materials including the inventor's disclosure of prior art.

[71] http://dellweb.bfa.nsf.gov/NSFHist_constant.htm Accessed 08/07/2014.

[72] The fifth NSF investment was a contract with a corporation to develop journal citation ranking measures. I have been unable to determine the amount of that contract and thus do not include it in these calculations.

[73] Padgett, John & Walter W. Powell. 2012. *The Emergence of Organizations and Markets.* Princeton Univesity Press.

[74] Johnson, Victoria & Walter W. Powell. 2014. "Poisedness and Propagation: Organizational Emergence and the Transformation of Civic Order in 19th-Century New York City." Working Paper: University of Michigan.

[75] *Ibid.* 1