The Endogeneity of Science: The Relationship of University Research to Industry and Innovation

by

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Abstract

This dissertation examines how the rate and direction of scientific science is endogenous to the institutional, technological and economic environment. The first essay investigates how local industrial R&D impacts the rate and direction of academic research by measuring the geographically localized spillover effect from industry R&D headquarters to nearby universities, which I call "reverse knowledge spillovers". To address the endogeneity concerns due to selection of industry location, this study exploits the exogenous entry into plant biotechnology R&D by pre-existing agribusiness incumbents in non-biotechnology clusters. I find that after the industry incumbents' entry into plant biotechnology R&D, colocated universities with the institutional capacity for industry boundary-spanning experienced a significant productivity increase in industry-relevant fields of science.

As a further investigation into the phenomenon of "reverse knowledge spillovers", the second essay examines the individual antecedents that incentivize university scientists to engage in industry-relevant research. I argue that young and less prominent scientists have a stronger incentive to exploit new opportunities provided by the local industry due to the lack of alternatives and less opportunity cost.

Finally, the third essay provides a theoretical overview of the endogeneity of science. The purpose of this essay is to deepen our understanding of Science as an economic institution, and to draw out some of the crucial pathways by which the structure, conduct and performance of the scientific research enterprise is endogenous to the institutional environment, technology and economic objectives.

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Contents

Chapter 1

Reverse Knowledge Spillovers from Industry to Academia: Evidence from the Agricultural Biotechnology Revolution

1.1 Introduction

What makes one region more innovative and entrepreneurial than others? It is widely claimed that universities are a key piece of infrastructure undergirding the growth of innovation and entrepreneurship in nations and regions, because university knowledge spillovers act as a magnet for agglomeration of innovative firms in science-based industry sectors (Audretsch and Feldman, 1996; Feldman and Florida, 1994; Hausman, 2012; Zucker et al., 1998). Many policy practitioners believe that the economic success of industrial clusters like Silicon Valley or Cambridge's biotechnology cluster can be replicated by cultivating universities such as Stanford and MIT. For example in 2011, New York City Mayor Bloomberg invited top-notch universities to enter the bidding for a new engineering and applied sciences campus to be built in Manhattan, with a hope of transforming the city into the next Silicon Valley.

A key underlying assumption in this line of research is that scientific research in academia is a pre-existing *input* for applied R&D and innovation in local industry, which appears exogenously or randomly with respect to the surrounding industrial environment. The seminal study of Zucker et al. (1998), for example, is grounded in the assumption that the rise of biotechnology clusters was driven by the exogenous distribution of academic human capital in biotechnology research, just as the growth of the mining industry has been shaped by the pre-determined distribution of natural endowments like precious metals and minerals.

On the other hand, historical anecdotes inform us that the reverse causality may also be true: the existence of R&D intensive industry drives the rise and growth of industry-relevant sciences at local universities in the region. For example, the existence of the tire and rubber industry in Ohio has shaped local universities like the University of Akron and Case Western to be the world leaders in rubber chemistry and polymer science research. The University of Washington in Seattle, which became the home to Microsoft Research in 1991, has grown to one of the world's best in computer science research during the past two decades.

Such co-evolution of local industry and academia are due to the existence of bilateral feedback between university science and industry technology (Etzkowitz et al., 1998; Murmann, 2013; Rosenberg, 1982). However, the knowledge spillovers literature has failed to incorporate this bilateral relationship and been almost entirely dominated by empirical analysis of the spillover effect from local academia to industry. I address the existing gap in the literature by shifting the focus to the reverse (*i.e.* from industry to academia) direction of the spillover effect, which I define as "reverse knowledge spillovers".

In lieu of just measuring the overall spillover effect, this study explores the organizational antecedents of reverse knowledge spillovers, by investigating at what types of universities experience a salient productivity boost due to reverse knowledge spillovers from the local industry. I hypothesize that a university will experience a greater spillover effect from local industry R&D if the university has the institutional infrastructure and normative system to support and facilitate active boundary-spanning between academia and industry, which I define as a university's "boundary-spanning capacity."

Empirically, disentangling the impact of local industry R&D on academic research from vice versa is challenging because companies select into places where they expect to benefit from academic knowledge spillovers. To overcome the endogeneity bias in industry location, one needs a setting in which there is an exogenous shock upon the direction of industry R&D, determined independently of existing academic research capacity in the region. The agricultural biotechnology industry is a suitable setting for this empirical strategy because the entry of incumbent agribusiness firms into agricultural biotechnology R&D provided an exogenous shock to the locations of their major R&D headquarters, which the firms had chosen and maintained since long before the rise of biotechnology when they were operating in non-biotechnology agribusinesses like agrichemicals and seed breeding. Using difference-in-differences and coarsened exact matching on a panel dataset of research-active academic institutions in the field of plant biotechnology between 1972 and 2009, this study carefully identifies the causal impact of industry R&D colocation upon the research output at the university level.

The results from fixed-effect Poisson regressions, run on a sample of coarsened-exact-matched universities, show that colocation with industrial R&D itself does not have a significant net positive impact upon local universities' research output in industry-relevant fields of science. However, the results from difference-in-differences-in-differences (DDD) find that the impact of local industry R&D is postively greater among universities with an early adopted (*i.e.* adopted prior to 1980) technology transfer office (TTO), a medical school or the land-grant status, which are proxies of boundary-spanning capacity.

After the entry of agricultural anchor tenants into plant biotechnology R&D, colocated universities which had an early adopted TTO experienced a dramatic increase in plant-biotechnology-related publications, which is greater than the change in outcome of colocated universities without an early TTO by 170%-204% (after having controlled for the TTO-specific trend). The change in plant biotechnology research output for colocated universities with a medical school and for colocated land-grant universities was greater than that of other colocated universities without it by 300% and 170%, respectively. This result is not driven by the fact that universities with such institutional capacity also tend to have strong research capacity. On the contrary, universities with strong research capacity (proxied by whether the university was one of the top 25% in pre-1980 NSF funding) experiend a 90% decline in plant biotechnology research output compared to those with weaker research capacity.

The findings of this paper show that only a subset of local academic institutions are significantly influenced by reverse knowledge spillovers, as reverse knowledge spillovers are mediated by the institutional capacity of individual institutions to engage in industry boundary spanning. Whereas previous research only considered the role of technology transfer offices and science parks in transferring academic knowledge to industry, this study induces us to rethink about their role as a two-way channel. Additional analyses shed light upon some of the underlying mechanisms behind the result: colocated universities with an early TTO engage in more active collaboration with industry, and develop stronger research interest in commercial crops. This confirms that entrepreneurial motivation plays a strong role in reverse spillovers. Additionally, I find that universities with a medical school or the land-grant status better explore new knowledge coming from the local industry, which implies that university-level absorptive capacity positively moderates the impact of reverse knowledge spillovers.

The paper is organized as follows. In Section 1.2, I review the literature on the endogeneity of academic science and provide theoretical frameworks and hypotheses. The empirical strategy and data are described in Section 1.3 and 1.4, followed by results in Section 1.5. I conclude by discussing the strategic implications of this study in Section 1.5.

1.2 Theoretical Background

1.2.1 The Endogeneity of Academic Science to Industrial Innovation and Technology

The role of university research as an engine for innovation and entrepreneurship has become the center of scholarly and policy discourses on regional development. Many researchers argue that academic knowledge is diffused or transferred to local industry for application and commercialization, acting as an important impetus for the growth of industrial innovation and entrepreneurship in the region (Anselin et al., 1997; Audretsch and Stephan, 1996; Hausman, 2012; Jaffe, 1989; Zucker et al., 1998). Based on this stream of research, many local governments have actively adopted policy plans to maximize the creation and diffusion of academic knowledge spillovers, such as offering campus space for top-tier universities and investing in university parks.

In studying the impact of geographically localized knowledge spillovers from academia to industry, most empirical studies have implicitly assumed academic knowledge in a region as a pre-determined input, which arises exogenously with respect to the surrounding industrial environment. Often overlooked or abstracted away in these studies is an understanding of academic science as an *output* of the industry environment. For example, in Zucker et al. (1998), the geographical distribution of academic stars is considered as exogenously determined and fixed in place. Although Jaffe (1989) and Anselin et al. (1997) acknowledge that industry R&D and university research can be simultaneously determined (*i.e.* university research is endogenous to private R&D) and take this into account in their econometric estimation, this endogeneity is considered as an identification challenge to be overcome, rather than a phenomenon whose underlying processes merit further investigation.

The treatment of academic knowledge as an exogenous input in the empirical literature may be (implicitly) driven by the traditional dominance of a linear model of science and technology, which regards academic science to be unilaterally shaping and supporting industry innovation (Bush, 1945)[1]. This model assumes that basic science in academia precedes applied R&D and innovation in the industry, ignoring that formation of scientific questions (even those that may seem basic under the dichotomy of basic vs. applied research) can be guided by simultaneous pursuit of industrial application (Rosenberg, 1982). This view has been strengthened by the political rhetoric of pure science, which considers applied research dependent on and inferior to basic research (Godin, 2006). According to this traditional view, basic research is considered to be solely guided by internal norms of academia, such as intrinsic motivations and peer-group esteem (Dasgupta and David, 1994).

In contrast, a group of scholars have emphasized the bilateral, co-evolutionary feedback from the external world to academic science (Etzkowitz et al., 1998; Murmann, 2013; Rosenberg, 1982). According to this view, the creation of scientific knowledge in academia is guided by technological needs of the industry, as well as overall socioeconomic concerns that may be external to the academic realm. Technological problems and empirical challenges in the industry pose new theoretical questions and shape the subsequent direction of academic research. This is backed by a number of anecdotal examples in the history of science. For example, the development of solid state physics as an academic discipline was driven by industry need to understand the transistor effect and to develop better semiconductors (Rosenberg, 1982). The rise of chemical engineering as an academic discipline built upon the concept of unit operations, which was first propounded by Arthur D. Little, an MIT alum and industrial chemist, as a way to design large-scale plants and equipment and streamline the processes in the chemical industry (Landau, 1991).

The endogeneity of academic science to industry also operates through pecuniary channels. Technological and practical needs in the private R&D shape academic research agenda by influencing the amount of research funding and job opportunities that get supplied into different fields of academia. The escalation of research expenditure, coupled with shrinking federal research support, led academic researchers to seek alternative sources of funding (Stephan, 2012). Industry may shape the agenda

[1] Godin (2006) provides a comprehensive review of the literature on the linear model of innovation.

of budget-constrained academics by selectively funding scientific research which are likely to result in technological innovations with high financial returns. The regulatory changes and institutional development that supported active academic patenting, technology transfer and academic spin-offs, such as the adoption of the Bayh-Dole Act, also motivated academic researchers to shift their research focus to questions of commercial interest (Azoulay et al., 2009; Sampat, 2006). Intensified competition for academic jobs may also lead job-seeking academics to favor industry-relevant research for higher job security.

1.2.2 Reverse Knowledge Spillovers from Local Industry to Academia

Although knowledge spillovers literature does acknowledge the bilateral nature of knowledge spillovers – that universities may also benefit from the local presence of innovative companies, the empirical literature is yet surprisingly devoid of studies that put forward the question of how industry-relevant academic knowledge in a region is brought about as a result of local industry presence.

Put differently, the question to be answered is to explore the positive (or negative) externalities of industry colocation upon university's research productivity. There are multiple channels through which local industry can influence the rate and direction of academic research. Industry presence can create significant externalities upon the production of academic science by being a consumer of or collaborator with local university research, supporting the formation of market for labor and ideas in the local economy.

The co-evolution of tire industry and polymer research in Ohio makes a good historical case to understand this phenomenon. Akron, Ohio has been the center of the U.S. tire industry since the late 19th century. BF Goodrich, Goodyear and Firestone were founded in Akron in 1870, 1898 and 1900, respectively. The local presence of the tire industry led local universities in the region to actively engage in rubber chemistry and polymer research[2]. The University of Akron opened the world's first academic rubber chemistry lab in 1909, and Case Western Reserve University became the first university to adopt the major polymer science and engineering department in the U.S in 1967.

In early 1940s, the U.S. government had a pressing need to ramp up the production of synthetic rubber, as the World War II cut off 90% of the supply of natural rubber. In response to the soaring demand, rubber companies in Akron, under the government initiative, engaged in active collaboration with the University of Akron scientists to mass produce synthetic rubber. Technological needs of the local industry clearly identified the direction of research for local scientists, and local university scientists were able to access and build upon the findings of more than 200 industry patents. Collaboration with the local industry not only allowed university researchers to acquire new knowledge and find novel scientific questions, but also to free-ride on company infrastructure and investment for their own research.

Even post-war, the strong presence of rubber industry in the local economy creates a strong local demand for engineering scientists in polymer science. Local universities respond to the demand by training more graduate and postdoctoral students, thus increasing the hiring of faculty researchers and boosting the overall productivity in polymer research at these universities. The opportunity to license patents based on academic discoveries to the industry is another incentive for university researchers to consider industry-relevant research. The local industry cluster, by thickening the market for ideas, will be able to influence the research direction of academics in the region who want to capitalize on their academic discoveries. Simply put, if the local presence of Firestone or Goodyear makes it easier for the University of Akron researchers to license their polymer technology patents or build start-ups based on them, they will have a stronger incentive to engage in polymer research with commercial potential, compared to non-local researchers in the similar field. Thus I hypothesize the following:

[2]Rubber is one of the mostly widely used kinds of natural polymer. Research efforts to produce synthetic rubber, for example, is essentially polymer science and engineering.

Hypothesis 1: Industrial R&D in a university's geographical proximity ("local industrial R&D") has a positive effect upon the university's research in industry-relevant fields of science.

In this paper, I focus on empirical measurement of such industry colocation externalities on the rate and direction of academic research output. In light of the fact that traditional knowledge spillovers literature focused on the direction from academia to industry, I call this "reverse (*i.e.* industry-to-academia) knowledge spillovers." This is a different concept from the conventional notion of pure, non-pecuniary knowledge spillovers, and should rather be viewed as an aggregate spillover effect of industry colocation on academic knowledge production that may occur through both pecuniary and non-pecuniary channels.

1.2.3 The Role of Boundary-Spanning Capacity in Reverse Knowledge Spillovers

Assuming that reverse knowledge spillovers do exist, the next important question is what types of universities are mostly likely to be influenced by industry spillovers. Just as firm characteristics like absorptive capacity, connectedness and firm size can determine the extent to which firms can best absorb university spillovers (Cohen and Levinthal, 1990; Lim, 2004; Acs et al., 1994; Cockburn and Henderson, 1998), the same logic may also apply to universities. Here, I particularly focus on the role of the institutional capacity of universities to foster industry boundary spanning.

A university's institutional characteristics[3] - such as the reward and evaluation systems, behavioral norms, and role expectations of academic scientists with regard to industry involvement - play a crucial role in the endogenous relationship between industry and academia by shaping the extent to which universities will engage in industry-relevant research and commercialization.

I use the term "boundary-spanning capacity" to encompass a university's institu-

[3]The term "institutions" here is used in a sociological sense and refers to the social structure and mechanisms within an organization. It should be distinguished from "academic institutions" or "educational institutions". In this study, I use the term "university" for the latter.

tional infrastructure and norms which facilitate and incentivize academic scientists to span the industry boundary and pursue industry-relevant research. In the organizational literature, boundary-spanning individuals refer to those that cross multiple organizational boundaries to acquire important resources and information from the external world (Aldrich and Herker, 1977; Friedman and Podolny, 1992; Tushman and Scanlan, 1981; Rosenkopf and Nerkar, 2001). In the academic realm, boundary-spanning activities of academic scientists include collaborating with industry in joint projects or contract research, filing academic patents and engaging in technology transfer, serving on scientific advisory boards, or joining ventures (Azoulay et al., 2009; Ding et al., 2013; Evans, 2010; Toole and Czarnitzki, 2007). Strong boundary-spanning capacity in universities consists of institutional elements that support these activities – such as tenure systems, norms, and culture that reward and acknowledge applied, commercial research and academic patenting; and an infrastructure that bridges academia and university, such as technology transfer offices, spin-off incubators, and industry collaboration/training programs.

Let me provide a quick comparison of Stanford University and Princeton University to illustrate how a high boundary-spanning university differs from a university of low boundary-spanning capacity. Stanford University, for example, is the epitome of an academic organization with strong boundary-spanning capacity. Stanford, which states in its founding mission that its purpose is ".. *to quality its students for direct usefulness in life* ..", is known for emphasizing practical, applied, and entrepreneurial research. From early on, Stanford has been an institutional pioneer in industry boundary spanning. As early as the 1950s, Stanford invited local industry scientists to teach university courses, opened the Stanford Industrial Park which became the home to high-tech companies such as General Electric and Hewlett-Packard, and implemented the "honors cooperative program", which allowed local companies to send their scientists to Stanford for collaboration and an advanced degree (Kargon and Leslie, 1994; Saxenian, 1996). Stanford's institutional strength in industry boundary spanning continues into the late 20th and 21st centuries, boasting a strong infrastructure that includes a technological transfer office active since 1969, an active startup accelerator/incubator(StartX), the Stanford Technology Ventures Program, etc. Such institutional capacity has allowed Stanford to become an entrepreneurial and flexible university that actively absorbs technological and scientific breakthroughs from the industry and incorporate them into their scientific inquiries (Lenoir, 2014).

In contrast to Stanford, Princeton University shows that strong research capacity does not always coincide with high boundary-spanning capacity. Princeton University has established its identity as a strong research university dedicated to advancing basic, upstream theory in major scientific disciplines, which can be implicitly deduced from its mission statement of "pursuit of excellence." Indeed, historical evidence suggests that Princeton has intentionally distanced itself from opportunities for industry boundary spanning. Although private laboratories based in New Jersey, such as Sarnoff Research Center of the Radio Corporation of America, Industrial Reactor Laboratories, and Bell Laboratories, wanted to collaborate with Princeton or establish graduate training programs at Princeton to suit their needs, their request was declined outright (Kargon and Leslie, 1994). Their lack of boundary spanning is also reflected in the fact that Princeton's technological transfer office only opened its doors in 1987 and the university only had 3 patents before the enactment of Bayh-Dole Act in 1980 (Stanford, in comparison, had already filed for 60 patents even before 1980).

As discussed in the anecdotes above, whereas a university with low boundary-spanning capacity will likely remain as a silo unconnected to the local industry environment, a university with strong boundary-spanning capacity provides multiple channels through which its researchers can engage with local industry. As a result, a university with strong boundary-spanning capacity can better hire and cultivate productive researchers in local industry-relevant domains of science.

> Hypothesis 2: Industrial R&D in a university's geographical proximity ("local industrial R&D") has a greater positive effect upon the university's research in industry-relevant fields of science, if the university has high boundary-spanning capacity.

1.3 Research Setting and Design

1.3.1 Identification Challenge

Only a small empirical literature cleanly identifies the industry-to-academia feedback by addressing issues of selection and endogeneity (Furman and MacGarvie (2007) is one of such few empirical works). The key identification challenge in measuring the impact of local industrial R&D upon academic research is the selection bias of "treated" universities and individuals (i.e. those that are colocated with industrial R&D). In general, entrepreneurs found R&D-intensive firms (or bigger firms locate their R&D unit) near universities whose academic scientists are already doing related research or have the potential for it ("selection effect"). Breakthrough research by university scientists also encourages colocated firms to pursue further follow-on R&D to exploit localized university knowledge spillovers ("reverse causality").

In an ideal experiment, one would randomly locate industrial R&D laboratories, independently of research quality or trajectory of academic researchers and institutions, then compare the impact of industry co-location upon the future evolution of academic research in the treated regions against the controls. Or, one would initiate a certain type of industrial R&D project in a randomly selected group of existing R&D locations and observe the evolution of local academic research in those regions.

Without the availability of such randomized experiments, an alternative empirical strategy to overcome this identification conundrum is to exploit a setting in which there is an exogenous shock upon the direction of industry R&D, determined independently of existing academic research capacity in the region. The agricultural biotechnology industry is a particularly suitable setting for this empirical strategy because the entry of incumbent agribusiness firms into agricultural biotechnology R&D provided an exogenous shock to the locations of their major R&D headquarters, which the firms had chosen and maintained since long before the rise of biotechnology when they were operating in non-biotechnology agribusinesses like agrichemicals and seed breeding.

Another commonly used empirical strategy to get around the endogeneity problem is to compare the treated universities with valid counterfactuals that would otherwise have followed the same trajectory in the output variable, after conditioning on observables (Greenstone et al., 2010). I combine the two identification strategies and explore my research questions in the setting of agricultural biotechnology industry.

1.3.2 The Empirical Context: The Agricultural Biotechnology Revolution

Agricultural biotechnology refers to a broad set of scientific and technological knowledge and techniques to improve the agricultural yield of plants and animals (for the purpose of this study, the focus will be specifically on plant biotechnology). The main tool in modern agricultural biotechnology is genetic engineering, which refers to manipulation of genetic elements to introduce into organisms new traits, such as resistance to disease, pest, or drought. Genetic engineering of plants started in 1977 when Belgian researchers at the University of Ghent first succeeded in transferring foreign genes into the plant genome, using *Agrobacterium tumefacien* (Moeen, 2013). Industry saw a huge commercial potential in agricultural biotechnology when the Supreme Court's 1980 ruling on Diamond vs. Chakrabarty allowed patenting of genetically engineered organisms. Soon after in the early 1980s, many companies subsequently started actively investing in agricultural biotechnology R&D.

The key feature of the agricultural biotechnology revolution is that the new technological discontinuity could not overturn the value of incumbent complementary assets – plant breeding techniques, germplasms, and the distribution network. Successful commercialization of genetically modified plants is impossible without these traditional assets. The hold-up of complementary assets, combined with the regulatory risk and inhibiting R&D costs, suppressed the role of new biotechnology firms (NBFs) in this industry. Although a number of de novo startups and greenfield subsidiaries were founded based upon university research in the early phase of the industry, they had a very limited role. Examples include de novo agricultural biotechnology startups like Calgene (founded in 1980 by Ray Valentine, a plant geneticist at University of California Davis) and Mycogen (founded in 1982 by Andrew Barnes, a biochemist in San Diego), as well as greenfield subsidiaries of diversifying entrants like Agracetus (founded in 1981 by the pharmaceutical biotechnology firm Cetus under the helm of Dr. Winston Brill, a microbiologist recruited from University of Wisconsin). Despite their scientific expertise, the growth of biotechnology-based ventures in this industry was largely constrained by the fact that genetic modification itself would not create value unless combined with the right type of plant breed (germplasms). For example, the first commercial GM crop product, Calgene's Flavr Savr tomato, ended up as a devastating failure because they lacked the complementary assets (Charles, 2001). Plant breeding takes time, patience and experience, and the time compression diseconomies (Dierickx and Cool, 1989) associated with plant breeding made it an important strategic resource which startups could not easily acquire.

Due to this industry feature, modern agricultural biotechnology was largely driven by the initiative of existing incumbent companies, which had both the technological prowess and the deep pockets to control both upstream R&D and downstream complementary assets, germplasms and seeds, which were the key resources in this industry. These incumbents were the traditional seed breeders and diversifying incumbents from other (broadly defined) agricultural industry, such as agrochemicals and animal health. Agrochemicals companies had a strong incentive to invest in agricultural biotechnology, as the new technology could serve as both a substitute for and a complement of their existing products. For example, genetically engineered plants such as Bt (*Bacillus thuringiensis*) corn can substitute the use of pesticides by producing natural insecticide (Bt Cry protein) that kills corn borers. Or, they could engineer plants to be sold as a bundle with their existing agrochemical product. Monsanto genetically engineered corn varieties that are resistant to their herbicide product Roundup (glyphosate), so that customers of Roundup can buy Roundup Ready Corn as a bundle, and not worry about herbicide affecting their crop product. The incumbent agrochemicals companies saw the potential and started researching new technology even ahead of major land-grant universities (Kenney, 1986).

Through an array of mergers, acquisitions and joint ventures over the recent several decades, a handful of diversifying incumbents have grown to dominate private R&D in this area in the United States. According to a USDA report by Fuglie et al. (2011), since 1982, the "Big 6" companies (Monsanto, DuPont, Syngenta, Bayer, Dow Agrosciences and BASF), which entered the agricultural biotechnology industry from agrochemicals, have been actively engaged in both internal R&D, as well as forward and backward vertical integration of the global value chain. They account for more than 70% of all U.S patents issued for crop cultivars, petitions for field trial with GM plants in the U.S and U.S. patents in agricultural biotechnology since 1982.

1.3.3 The Five "Anchor Tenant" Locations

Because of such difference in industry structure, the geographical distribution of agricultural biotechnology R&D has a very distinct pattern from that of medical biotechnology. In the case of medical biotechnology, the birth of the industry followed or coincided with the rise of academic science and academic spin-offs based on university research. On the contrary, agricultural biotechnology R&D has been heavily concentrated among a select number of locations where the incumbent companies had maintained their R&D operations in non-biotechnology agribusiness since long before the advent of biotechnology. The locational inertia in agricultrual R&D kept incumbent firms at or near their traditional R&D locations even after the technological discontinuity. Because of a greater focus upon in-house R&D (rather than external sourcing) combined with locational inertia, these companies did not relocate their R&D activities despite their transition to new areas of R&D and the increasing dependence upon academic science.

Using the terminology in Agrawal and Cockburn (2003), I refer to these companies as "anchor tenants", because these anchor tenants create significant externalities upon local economies by being large, old, locally-based and R&D intensive. Anchor tenants function as both a consumer and an investor of university research, as well as supporting the formation of the market for ideas and thickening the labor market (Agrawal and Cockburn, 2003).

Such anchor tenants include traditional seed breeders as well as diversifying incumbents from other (broadly defined) agricultural industry, such as agrochemicals and animal health that had been conducting non-biotechnology agricultural R&D since long before 1980. As they had been previously operating in non-biotechnology industries since long before the inception of agricultural biotechnology, their locations had been chosen for reasons that are mostly exogenous to the development of academic research in modern biotechnology. In other words, the central R&D locations of the incumbent companies were determined independently to the availability of university scientists in biotechnology-related disciplines.

Insert Table 1.1 & Figure 1-1 about here

In the paragraphs to be followed, I identify and explain the major anchor tenant locations that I will be examining in my empirical analysis.

Monsanto-St.Louis. Monsanto is one of the biggest multinational agrochemicals and agricultural biotechnology companies in the world. John Francis Queeny founded Monsanto with the idea of saccharine manufacturing in St. Louis in 1901. Before its entry into genetic engineering, it had diversified into pesticides, diodes and plastics. Its main product in the agricultural business was the herbicide Roundup (glyphosate), which so far has been one of the most widely used herbicide in the U.S. In 1981, a molecular biology group was set up and biotechnology was established as Monsanto's strategic research focus. Ever since, Monsanto has been one of the most active players in the plant biotechnology R&D race and now the world's biggest seed company, controlling 27% of the proprietary seed market as of 2013. Although Monsanto as a whole operates multiple R&D sites after the acquisition of Calgene, Agracetus and Dekalb, Monsanto's main R&D headquarters has remained in Chesterfield, right next to its original founding location in St. Louis.

Du Pont-Wilmington. E.I. du Pont de Nemours and Company, henceforth Du Pont, was founded in 1802 near Wilmington, Delaware as a gunpowder manufacturer.

It had chosen that location because of easy access to waterpower and trees (Furman and MacGarvie, 2009). It diversified into other areas of business in the early 20th century, exploiting its capability in chemicals. The company was in the agrochemicals business since 1928, mainly as a manufacturer of herbicides and pesticides. In the early 1980s, the company entered into agricultural biotechnology R&D about the same time as Monsanto and is now a member of the "Big 6" (Monsanto, Du Pont, Syngenta, BASF, Bayer, Dow) in the global seed industry. Du Pont's agricultural R&D has been conducted in the Du Pont Experimental Station in Wilmington.

Ciba Geigy/Syngenta-RTP. Ciba-Geigy is a predecessor of Syngenta in the early 1980s. Ciba-Geigy was originally a Swiss-based multinational chemicals company, born after the merger of Ciba and Geigy. The U.S. agricultural division of Ciba-Geigy Chemicals has been located in Greensboro, North Carolina since the early 1970s. Ciba-Geigy entered plant biotechnology R&D in 1983, setting up a biotechnology laboratory in Research Triangle Park (RTP), proximate to its original agrichemicals division in Greensboro. Although Ciba-Geigy's new location was chosen to have a long-term presence near the RTP's research universities, cutting-edge plant biotechnology was not immediately available in RTP at the point of entry. Instead, they hired as their principal scientist Mary-Dell Chilton, a renowned plant biotechnology researcher at Washington University in St. Louis. Ciba-Geigy was later merged with Sandoz to form Novartis, then its agricultural biotechnology business was spun off as Syngenta.

Pioneer Hi-Bred-Johnston. Pioneer Hi-Bred, a breeder and distributor of hybrid corn, was founded in Des Moines, Iowa in 1926. It had been the leading expert in traditional breeding and cross-hybridization and owned seed germplasms, the complementary asset to genes. Pioneer Hi-Bred established a (molecular) plant biotechnology team in 1989. It was acquired by Du Pont in 1999, but it has remained active in research in its original location. Its R&D site has been located in Johnston, Iowa near its original founding location.

(Dow)Elanco-Indianapolis. Elanco is the agricultural division of Eli Lilly and Company, a major pharmaceutical company based in Indianapolis since the 1870s.

Formed in 1954, Elanco's main business had been veterinary pharmaceuticals as well as agrichemicals such as insecticide, herbicide, and fertilizers. In 1989, Elanco's full-fledged engagement in plant biotechnology research took off when its plant science division entered into joint venture with the Dow Chemical Company. Although Eli Lilly divested out of the DowElanco partnership in 1997 and it became Dow Agrosciences of today, its R&D headquarters has been based in Indianapolis since Elanco's founding in 1954. Dow Agrosciences grew to be one of the Big 6 of the agricultural biotechnology industry, acquiring Mycogen and Cargill's North American seed business.

1.3.4 Identification Strategy: Difference-in-differences & Coarsened-Exact-Matching

In order to measure the impact of local industrial R&D upon the rate and direction of academic science, I first use a difference-in-difference estimation strategy which compares the change in industry-colocated academics' research output to the changes of a comparable group that are not colocated with industry R&D. In order to make sure that both treated universities and academics are compared to a valid group of counterfactuals, I employ coarsened-exact-matching on a number of observable characteristics as well as the pre-treatment outcome.

Colocation with these anchor tenants can be considered as an unconfounded assignment for universities (*i.e.* exogenous to the universities' research capacity in agricultural biotechnology), because the following identification assumptions are met: 1) The drivers of locational decisions for non-biotech agribusiness are unrelated to academic research in agricultural biotechnology, 2) When choosing the R&D locations, the anchor tenants did not anticipate their future transition from non-biotech agribusiness to agricultural biotechnology, nor the need to build on local academic research in agricultural biotechnology.

Another crucial identification assumption is 3) the anchor tenants' decision to enter into agricultural biotechnology and maintain their R&D in the original location was not driven by regional characteristics or region-specific shocks in favor of agricultural biotechnology research. In order to alleviate this concern, I paired treated universities to a set of coarsened-exact-matched controls that are comparable on observable characteristics, and have parallel trends in research output prior to the treatment. For the matching criteria, I used 1) the average annual student body, 2) the average amount of annual NSF funding, 3) the average amount of annual USDA funding, 3) the cumulative number of plant biotechnology publications, 4) land grant status, 5) the existence of an agricultural sciences department, and 6) the existence of the genetics department up to the year of treatment.

I coarsened the joint distribution of the covariates by breaking the continuous variables into separate bins (cut-off values at 25th, 50th, 75th, 90th, 95th and 99th percentile) and keeping the strata that contained one treated university and at least one control. I implement the CEM procedure before each treatment year (1981, 1982, 1984, 1989) without replacement, trimming the number of observations from 500 to 238 universities. The number of control units to treated units varies from strata to strata. Because my CEM results in one-to-many matches, I hand-calculated and assigned the appropriate weights for each observation so that a weight of 1 is assigned to each treated unit and T_i/C_i (number of treated observations in the strata/controls in the strata) to each control unit in the strata (Iacus et al., 2012). The fixed effect regressions are weighted by the individual weights assigned in the CEM procedure.

1.3.5 Econometric Specification

The main empirical strategy of this study is difference-in-difference estimation. Academic organizations (universities) colocated with the R&D headquarters of these five anchor tenants are considered to be have been "treated" (using the language of quasi-experimental research), after the colocated firm's entry into plant biotechnology. The impact of industry R&D on the treated universities will be compared against controls which are comparable on observable characteristics. I identify the controls by using coarsened exact matching (Iacus et al., 2012), an empirical approach which remedies the endogeneity of treatment variable by balancing the treated and control observations on exogenous variables.

The unit of analysis is university-year. The econometric specification at the university level is a difference-in-differences-in-differences estimation (DDD), an extension of a difference-in-differences estimation.

$$Publication_{i,t} = f(\epsilon_{i,t}; \alpha_i + \beta_t + \delta Coloc_i \times \textit{Post-Entry}_{i,t}) \tag{1.1}$$

$$\begin{aligned} Publication_{i,t} = f(\epsilon_{i,t}; \alpha_i + \beta_t + \delta Coloc_i \times \textit{Post-Entry}_{i,t} + \rho \textit{Boundary-Spanning}_i \times \\ \textit{Post-Entry}_{i,t} + \mu \textit{Boundary-Spanning}_i \times \textit{Post-Entry}_{i,t} \times Coloc_i) \end{aligned} \tag{1.2}$$

Boundary-Spanning$_i$ is a dummy variable coded as 1 if university i has strong boundary-spanning capacity prior to the treatment (*e.g.* if the university had a technology transfer office before 1980, if the university has a medical school, or if the university is a land-grant university). $Coloc_i \times \textit{Post-Entry}_{i,t}$ is a dummy variable that equals 1 for treated universities, only in those years after the company colocated with the treated university entered into plant biotechnology R&D. $Coloc_i \times \textit{Post-Entry}_{i,t} \times \textit{Boundary-Spanning}_i$ is a dummy variable that equals 1 for treated universities that have strong boundary-spanning capacity, only in those years after the company colocated with the treated university entered into plant biotechnology R&D.

The coefficient δ we obtain from the regression can be interpreted as the expected change in outcome that treated universities without strong boundary-spanning capacity will experience. ρ can be interpreted as the expected change in outcome that control universities with strong boundary-spanning capacity will experience. Most importantly, the coefficient of interest μ captures the impact of local industrial R&D upon high-boundary spanning universities after netting out the effect of high boundary-spanning capacity upon universities in non-treated regions.

If we omit the $\textit{Boundary-Spanning}_i \times \textit{Post-Entry}_{i,t}$ from the estimation equation, μ will estimate the difference in treatment effect between high-boundary-spanning universities and low-boundary-spanning universities in treated regions only. This does not take into account that high-boundary-spanning universities in general can have a different trajectory in their publication trend vis-à-vis low-boundary-spanning universities.

As the dependent variable is a nonnegative count variable with skewed distribution, I use the conditional fixed-effect Poisson model with QML (quasi-maximum-likelihood) standard errors clustered at the university level. According to Wooldridge (1997), QML ("robust") standard errors are robust to the issues of serial correlation raised by Bertrand et al. (2004).

1.4 Data and Variables

1.4.1 Sample

My sample of universities comes from the NSF Survey of Graduate Students and Postdoctorates in Science and Engineering (GSS survey) between 1972 and 2009. In the case of public university systems which include separate and distinct academic institutions that operate in multiple campuses, such as the University of California or the University of Texas, each stand-alone university is counted as one unit of observation. I dropped from the initial sample professional and special-purpose schools such as seminaries, military schools, osteopathic or dental schools, as well as schools located in Puerto Rico. I further trimmed the sample by only examining research-oriented schools that have been active in the realms of scientific research and publishing: Research I, Research II, Doctorate-Granting I, Doctorate-Granting II and Comprehensive I schools under the Carnegie Classification of 1987 were kept in the sample[4]. The coarsened exact matching brings the number of sample down from 398 universities to 186 universities (a matching rate of about 47%).

[4] I used the 1987 Carnegie Classification as that is the oldest report that is available online (the first report was in 1973).

1.4.2 Variables

Dependent Variables

Publication output in plant-biotechnology related sciences. The dependent variable of interest is the university's publication output that is relevant to industrial R&D in plant biotechnology. The easiest way to collect the data for this dependent variable is to gather all publications in journals that specifically focus on plant biotechnology. However, this comes at a cost of missing relevant articles that are published in journals of a broader discipline, such as Plant Physiology and the Journal of Biological Chemistry. In order to gather all relevant articles regardless of the journal's disciplinary orientation, I use the following two-step procedure: I first downloaded titles and abstracts from the top three journals in the field of plant molecular biology and genetics: Plant Cell, Plant Molecular Biology and Plant Biotechnology Journal. By using a text-mining process[5], I extracted a set of essential keywords that are relevant to sciences of plant biotechnology and repeatedly appear in these articles. Then I applied the combination of these keywords to search Web of Science to download all publications which contain the keywords in their title or abstract. Table 2 shows that plant biotechnology research appears across many journals, including non-plant biotechnology specific journals. I identified author addresses in these articles to aggregate them at the university level.

Insert Figure 1-2 & Table 1.2 about here

Explanatory Variables

Colocation with Industry R&D. As mentioned in the previous section, I identified the loci of treatment as the following five locations: Monsanto Headquarters in Creve Coeur, Missouri; Du Pont Experimental Station in Wilmington, Delaware;

[5] I used the online text-mining tool called TerMine, available at http://www.nactem.ac.uk/software/termine/.

Ciba Geigy (now Syngenta)'s Agricultural Biotechnology Research Center in Research Triangle Park, North Carolina; Pioneer Hi-Bred (now part of Du Pont) Headquarters in Johnston, Iowa; DowElanco (now Dow Agrosciences) Headquarters in Indianapolis, Indiana. I identified the exact location of the main R&D laboratory by cross-checking the Directory of American Research and Technology and the author addresses in company publications.

I considered universities within a 100-mile radius of these locations as geographically proximate to a locus of industrial R&D (*i.e.* colocated with the company), as suggested in Furman and MacGarvie (2009). The treatment is considered to have taken place when the colocated company entered into plant biotechnology R&D by launching an official internal unit or a joint venture dedicated to plant biotechnology (*e.g.* Monsanto in 1981, Ciba Geigy in 1984, Pioneer in 1989, DowElanco in 1989). In the case of Du Pont, I could not date the official launching of a plant biotechnology team from official sources, although it is known that it entered the industry around the same time as Monsanto. Instead, I take 1982, when Du Pont first published an academic paper in the topic of plant molecular genetics, as the treatment year.

Strength of University's Boundary-spanning Capacity. My hypothesis states that the impact of industry R&D will affect a colocated university when its researchers have access to boundary-spanning institutions that facilitate and incentivize university-academia interactions. I use several proxy measures for the strength of a university's boundary-spanning capacity: (1) the existence of a technology transfer office (TTO) before 1980, (2) the existence of a medical school at the university, and (3) the land-grant status of the university.

The fact that a university had an active TTO before 1980, even prior to the enactment of the Bayh-Dole Act which opened the era of academic patenting, suggests that the university has had an exceptionally strong culture and infrastructure that supported research commercialization. Such universities are likely to have had high experience in technology transfer services and industry collaboration, which will further facilitate and incentivize boundary spanning by academic scientists into industry. Having a medical school also has a similar implication, in that it is the earliest form of institutional innovation that incentivized practical, applied and technological research even before the advent of biotechnology (Rosenberg, 2009). Land-grant status counts as a proxy of boundary-spanning capacity in this particular industry context because land-grant status had been given with the mission to focus on practical agriculture and engineering.

These institutional features suggest that a university had early exposure to technology transfer and industry collaboration and is likely to have built a more systematic infrastructure to further aid subsequent industry boundary-spanning. Thus, the universities with higher initial boundary-spanning capacity are likely to exhibit subsequent development of boundary-spanning capacity and a faster shift into industry-relevant research compared to their counterparts.

Control Variables

I collected university-level data from the NSF Survey of Research and Development Expenditures at Universities and Colleges, as well as the NSF Survey of NSF Survey of Graduate Students and Postdoctorates in Science and Engineering. I used a set of university-level variables to match control universities to the set of treated universities. I include university-level controls and career age indicator variables (binned in 10 year intervals) in university-level fixed-effect regressions. Regional shocks may also affect the evolution of agricultural biotechnology research. For example, the Midwest or the Southeastern region have a natural advantage for important commercial crops such as maize, soybean and cotton, and the federal and state governments may provide disproportionate funding and incentives for universities in these regions. In order to control for such region-specific shocks, I include region-year interactions.[6]

[6] NSF survey categorizes university location into 9 regions (1: East North Central/Great Lakes Region (Illinois, Indiana, Michigan, Ohio, Wisconsin), 2: East South Central Region (Alabama, Kansas, Mississippi, Tennessee), 3: Middle Atlantic Region (New York, New Jersey, Pennsylvania), 4: Mountain Region (Arizona, Colorado, Indiana, Montana, New Mexico, Nevada, Utah, Wyoming), 5: New England Region (Connecticut, Massachusetts, Maine, New Hampshire, Rhode Island, Vermont), 6: Pacific Region (California, Hawaii, Oregon, Washington), 7: South Atlantic Region (DC, Delaware, Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia), 8: West North Central/Plains Region (Iowa, Kansas, Minnesota, Missouri and Nebraska) and 9: West South Central Region(Arkansas, Louisiana, Oklahoma, Texas)). I interact these variables with the Post-Entry indicator and include the interaction terms in the regressions.

1.5 Results and Analysis

1.5.1 Descriptive Statistics

The descriptive statistics of 186 universities in my final sample are presented in Table 1.3. Table 1.3 confirms that my CEM (coarsened exact matching) procedure resulted in a balanced match of treated and control universities, so that there is no significant difference between the sample moments of the two groups. Matching on the R&D expenditure funded by public sources (NSF and USDA), student body, land grant status and the existence of an agricultural sciences and genetics department have also achieved a balance across other observable covariates that were not included in the matching criteria.

Insert Table 1.3 about here

1.5.2 Main Result

Table 5 presents the fixed effect Poisson regression estimates of the impact of local industry R&D upon universities' plant biotechnology-related publications. All models include university fixed effects and year effects, which control for the university's time-invariant unobservables that are correlated with the treatment status and may affect the publication outcome. Robust (QML) standard errors were clustered at the level of the university. Because I use university fixed effects, time-invariant interaction variables are dropped from the model.

Insert Table 1.6 about here

The first column in Table 1.6, Model 1 explores the overall impact of industry R&D colocation upon the research outcome of universities. Without distinguishing the different types of universities, local industry R&D has a very small negative and insignificant upon the outcome variable. In other words, treated universities that were in the geographical proximity of industrial R&D did not produce more plant biotechnology-related publications compared to non-colocated universities in overall.

Model 2 through Model 4 include interaction terms between university-level characteristics and industry impact. The purpose of this model is to identify differential effect of treatment for the treated universities with high boundary-spanning capacity, which will be equivalent to μ in the estimation equation. The coefficient on *Colocation*Post-Entry*Early TTO* in Model 2 is positive and significant, which means that the effect of local industrial R&D is positive and significant for universities which had a technology transfer office prior to 1980. After the entry of the anchor tenants into agricultural biotechnology R&D, the increase in plant biotechnology publications experienced by the colocated universities with an early TTO was about 170%[7] greater than the increase in the outcome of colocated universities without an early TTO. In a similar specification, Model 3 shows that colocated universities that had a medical school experienced a boost in plant-biotechnology publication outcome, which is 198% greater than the change experienced by colocated universities without a medical school. Model 4 shows that having a land grant status results in less publication output for colocated universities, but this is reversed in the full model.

Model 6 enters all the interaction terms in Model 2 through 4, as well as the interaction of industry R&D colocation and the dummy for being top 25% in pre-1980 NSF funding, which is shown in Model 5. The dummy for NSF funding status is included in order to adjust for the fact that universities with early TTOs, a medical school or land grant status also tend to be more research-intensive universities in general. The result in Model 5 and 6 shows that industry-colocated universities that are also top research schools in terms of NSF funding experience a relative decline in the plant biotechnology publication outcome. This can be interpreted that universities that do not have an existing competitive advantage in research tend to respond more

[7]This incident rate ratio is calculated by exponentiating the Poisson coefficient and subtracting $1(e^{0.992} - 1 = 1.696)$.

actively to the new opportunities that arise from the local industry.

The full model supports Hypothesis 2, which argues that boundary-spanning capacity plays a significant role in promoting industry-relevant research at colocated universities. According to the full specification, colocated universities with an early TTO experienced a change in plant biotechnology publication which is 204% greater than the change in the outcome of colocated universities without an early TTO. For colocated universities with a medical school or land grant status, the change is greater by 300% and 177% by those without, respectively.

On the other hand, the coefficients on *Post-Entry*Colocation* are not positive and significant, suggesting that local industrial R&D has a positive impact only upon universities with strong boundary-spanning capacity. This supports my argument that university's response to local industrial R&D depends upon whether the university has an institutional system that incentivizes and facilitates boundary spanning by researchers across the industry boundary.

To address the concern that the result could have been driven by the general upward trend in research capacity that high-boundary-spanning universities in colocated regions may have experienced, I ran placebo regressions with the outcome variable being NSF funding and NIH funding. The results show that high-boundary-spanning universities in colocated regions did not experience an increase in NSF funding and NIH funding, assuring that the increase in plant-biotechnology-related research was not driven by a common trend.

1.5.3 Mechanisms

Table 1.5 and 1.6 take a look into the intermediate outcomes of industry R&D colocation to better understand the mechanism of industry-driven change. Model 1 of Table 6 presents the result for a pooled OLS regression of the logged sum of industry coauthored plant-biotechnology publications. I employ pooled regression instead of university fixed effect regression, because most variation in industry coauthorship exists across universities, rather than within. The existence of an early TTO seems to be a valid proxy of boundary-spanning capacity which promotes industry-colocated universities' collaboration with the industry. On the other hand, the interaction of colocation with land grant and medical school is not statistically significant. Land-grant universities seem to be able to coauthor with the industry, regardless of colocation. Model 2 shows a similar result for plant biotechnology publication related to major commercial crops (soybean, maize and cotton). Consistent with Model 1, interaction of colocation and early TTO is significant and positive, implying that industry can shift the direction of local academic research towards more commercializable areas.

Table 1.6 looks at whether local industrial R&D can widen the scope of academic research by providing new knowledge opportunities, and which types of institutions have been responsive to them. The dependent variables are the number of new field entries and journal entries that occurred through plant biotechnology research. New field entries and journal entries are defined as instances in which a university publishes a plant biotechnology publication in a web of science category or a journal where its previous plant biotechnology publications have never been published. The coefficients on *Post-Entry**Colocation*Medical* and *Post-Entry**Colocation*Land* are positive and significant, implying that new knowledge opportunities are captured by colocated universities that have a medical school or land-grant status.

Insert Table 1.5 & 1.6 about here

1.6 Discussion and Conclusion

Although there has been a long discussion on the endogeneity of science to the socioeconomic and industrial environment, most empirical studies have considered academic knowledge as an exogenous input to the local industrial environment. First, this gap in literature is driven by the fact that empirical researchers have not fully grappled with the issue of endogeneity bias in measuring the impact of industry on academia. As a result, the co-evolution of industrial sector and academic discipline has been examined mostly through case studies and descriptive statistics (Murmann, 2013;

Rosenberg, 1982).

To my knowledge, this is the first empirical study to systematically disentangle the impact of industrial R&D upon academia from the reverse impact. This study provides a novel empirical strategy to address the endogeneity of industry R&D location, which is to exploit old anchor tenant locations which had been pre-determined without regard to local academic capacity in the new focal field of research and maintained by locational inertia, in combination with an external shock which induces those firms to change their direction of R&D.

This study contributes to the body of research on university-industry relations by shedding light upon the phenomenon of industry-driven change in academic science. I provide empirical evidence for my argument that reverse knowledge spillovers from industry do not globally influence all universities, but instead impact a select group of universities that are deeply embedded in the industrial environment through geographical proximity and institutional support.

The findings of this study have a practical implication for local policymakers and university officials who want to foster innovation-based entrepreneurship in a region. Geographical proximity is not a sufficient condition for local universities' co-evolution with the industry cluster, and organizational infrastructure is necessary for engaging local universities in the endogenous and bilateral process. Whereas previous research only considered the role of organizational infrastructure like technology transfer offices and science parks to as a one-way channel from academia to industry, this study induces us to rethink about their role as a two-way channel.

At this stage, this study leaves room for further research and refinement. First, additional data is needed to nail down the functioning of actual micro-mechanisms that motivate the academic researchers to consider industry-relevant fields of science as their research topics. I discussed in my hypothesis development a number of possible mechanisms such as increased industry funding, job opportunities and entrepreneurial motivations. It would be useful to understand which mechanisms have a meaningful effects and their magnitudes.

Also, although I have shown that industrial R&D shapes academic research towards an industry-relevant orientation, whether that shift comes at a cost of other research is a separate issue. I hesitate to make any overall welfare judgment about the impact of industrial R&D from this study, such as whether the rise of industry-relevant science in a given region comes at a cost to other scientific fields in that region. This issue will be a topic for further research.

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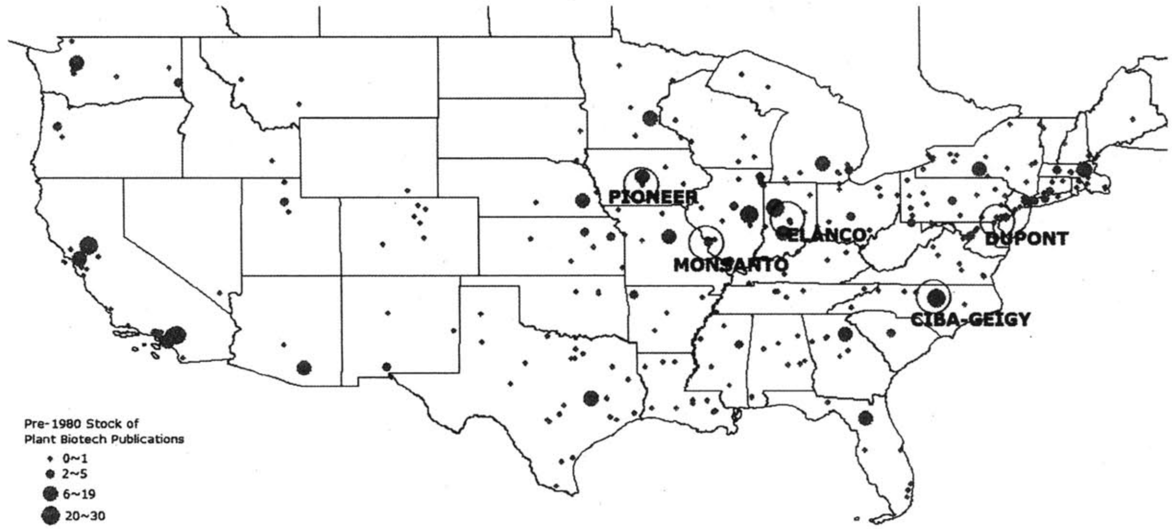
Figure 1-1: Big 5 Location and Distribution of Plant Biotechnology Research Prior to 1980



Note: Each green dot is a university, whose size is proportional to the stock of plant biotechnology publications prior to 1980. Red circles mark the location of Big 5 R&D headquarters.

Figure 1-2: Examples of Plant Biotechnology Publications

Evaluating the Performance of Transgenic Corn Producing Bacillus thuringiensis Toxins in South Carolina

By: Reay-Jones, F. P. F.; Wiatrak, P.; Greene, J. K.
JOURNAL OF AGRICULTURAL AND URBAN ENTOMOLOGY Volume: 26 Issue: 2 Pages: 77-86 Published: APR 2009

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A transformation booster sequence (TBS) from Petunia hybrida functions as an enhancer-blocking insulator in Arabidopsis thaliana

By: Hily, Jean-Michel; Singer, Stacy D.; Yang, Yazhou; et al.
PLANT CELL REPORTS Volume: 28 Issue: 7 Pages: 1095-1104 Published: JUL 2009

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Supplemental control of lepidopterous pests on Bt transgenic sweet corn with biologically-based spray treatments

By: Farrar, Robert R., Jr.; Shepard, B. Merle; Shapiro, Martin; et al.
JOURNAL OF INSECT SCIENCE Volume: 9 Article Number: 8 Published: MAR 19 2009

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Glyphosate and glyphosate-resistant crop interactions with rhizosphere microorganisms

By: Kremer, Robert J.; Means, Nathan E.
EUROPEAN JOURNAL OF AGRONOMY Volume: 31 Issue: 3 Special Issue: SI Pages: 153-161 Published: OCT 2009

Get this – MIT S·F·X View Abstract

Genetically Engineered Plants and Foods: A Scientist's Analysis of the Issues (Part II)

By: Lemaux, Peggy G.
ANNUAL REVIEW OF PLANT BIOLOGY Book Series: Annual Review of Plant Biology Volume: 60 Pages: 511-559 Published: 2009

Get this – MIT S·F·X View Abstract

Table 1.1: Summary of the Five Anchor Tenants

	DuPont	Monsanto	Pioneer Hi-Bred	Ciba Geigy	Elanco
Origin	Agrichemical	Agrichemical	Seed	Agrichemical	Veterinary Medicine/Agchemical
HQ	Delaware	Missouri	Iowa	N. Carolina	Indiana
In HQ Since	1802	1901	1926	1972	1954
Reason for HQ Location	Cheap Land and Water	Founder's Previous Job	Founder's Family	Dye/Chemical Division Relocation	Mother Company (Eli Lilly)
Biotech Entry	1982	1981	1989	1984	1989
Now			DuPont-Pioneer	Syngenta	DowAgrosciences

Table 1.2: Top 15 Journal Outlets for Plant Biotechnology-related Research

Journal Name	Count	%
Plant Physiology	2,770	6.94
Crop Science	1,780	4.46
Plant Cell	1,644	4.12
Proceedings of the National Academy of Sciences	1,641	4.11
Theoretical and Applied Genetics	1,537	3.85
Plant Journal	1,269	3.18
Plant Molecular Biology	1,260	3.16
Genetics	893	2.24
Phytopathology	754	1.89
Molecular Plant-Microbe Interactions	673	1.69
Journal of Biological Chemistry	668	1.67
Virology	550	1.38
Plant Disease	547	1.37
Total (All Journals)	39,914	100

Table 1.3: T-Test of Treated Universities and Control Universities' Pre-Treatment Characteristics

Treated Universities	Control Universities	Difference	T-stat (P-value)	
Pub Count (Flow)	0.57(0.29)	0.57(0.24)	0.01(0.50)	0.02(0.986)
Land-grant	0.20(0.07)	0.20(0.05)	-0.00(0.12)	-0.00(0.998)
Medical	0.18(0.06)	0.28(0.05)	-0.10(0.09)	-1.02(0.309)
Public	0.64(0.08)	0.75(0.46)	-0.11(0.10)	-1.06(0.290)
Student Body	653.1(165.5)	706.4(181.7)	-53.4(310.9)	-0.17(0.864)
USDA funding	2019.17(870.12)	1621.77(571.52)	397(1382)	0.29(0.774)
NSF funding	1505.55(500.46)	1583.62(458.82)	-77.96(769)	-0.10(0.919)
NIH funding	3304.43(1330.34)	6865.57(2476.50)	-3561(3077)	-1.16(0.249)
Agri. Dept	0.20(0.07)	0.20(0.06)	-0.00(0.13)	-0.03(0.976)
Genetic Dept	0.20(0.06)	0.15(0.05)	0.05(0.07)	0.69(0.492)
Botany Dept	0.25(0.08)	0.24(0.06)	0.01(0.13)	0.10(0.922)
Early TTO	0.14(0.05)	0.14(0.06)	1.09(5.70)	-0.00(0.998)
	34 universities	152 universities		

Note: Weighted mean (SD) reported.

Table 1.4: Fixed Effect Poisson Regression of Plant Biotechnology Publications between 1972-2009

	(1) Colocation Only	(2) Colocation * Early TTO	(3) Colocation* Medical	(4) Colocation* Land	(5) Colocation* Top NSF	(6) Colocation* Full Model
Post-Entry*Colocation	-0.002	-0.425	-0.208	0.734	1.169	0.832
	(0.281)	(0.315)	(0.332)	(0.271)***	(1.135)	(1.177)
Post-Entry*Early TTO		-0.341				-0.391
		(0.218)				(0.364)
Post-Entry*Colocation*Early TTO		0.992				1.115
		(0.407)**				(0.502)**
Post-Entry*Medical			-0.163			-0.022
			(0.161)			(0.162)
Post-Entry*Colocation*Medical			1.092			1.386
			(0.412)***			(0.516)***
Post-Entry*Land				-0.086		-0.166
				(0.200)		(0.341)
Post-Entry*Colocation*Land				-0.814		1.019
				(0.434)*		(0.533)*
Post-Entry*Top 25% NSF					-0.686	-0.482
					(0.368)*	(0.476)
Post-Entry*Colocation*Top NSF					-1.186	-2.388
					(1.178)	(1.208)**
University FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES

Post-Entry*Region Dummy	YES	YES	YES	YES	YES	YES
Obs	5,542	5,542	5,542	5,542	5,542	5,542
Group	146	146	146	146	146	146
Log Likelihood	-4,828.17	-4,818.91	-4,821.97	-4,822.76	-4,822.93	-4,808.93

Notes: Poisson regression coefficients with QML robust standard errors clustered at the university level in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table 1.5: Pooled OLS Regressions of Industry-related Outcomes

	(1) Logged Sum of Industry Coauthored Publications	(2) Logged Sum of Commercial Crop Publications
Colocation	0.002	-0.118
	(0.114)	(0.090)
Early TTO	0.142	-0.188
	(0.157)	(0.243)
Colocation* Early TTO	1.170	1.694
	(0.549)**	(0.774)**
Medical	0.231	0.236
	(0.203)	(0.249)
Colocation*Medical	-0.117	-0.284
	(0.440)	(0.278)
Land	1.513	1.821
	(0.414)***	(0.517)***
Colocation*Land	-0.298	0.091
	(0.491)	(0.596)
Top 25% NSF	0.221	0.418
	(0.319)	(0.446)
Colocation*Top NSF	0.332	0.219
	(0.691)	(0.714)
Obs	182	182
R^2	0.75	0.73

Notes: OLS regression coefficients with robust standard errors clustered at state level in parentheses. *$p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table 1.6: Fixed Effect Poisson Regressions of the New Field and Journal Entry

	(1) New Field Entry	(2) New Journal Entry
Post-Entry*Colocation	1.458	0.636
	(1.127)	(1.176)
Post-Entry*Early TTO	0.057	-0.300
	(0.253)	(0.308)
Post-Entry*Colocation*Early TTO	-0.570	0.246
	(0.649)	(0.591)
Post-Entry*Medical	-0.381	-0.322
	(0.153)**	(0.184)*
Post-Entry*Colocation*Medical	1.331	1.312
	(0.518)**	(0.522)**
Post-Entry*Land	-0.372	-0.697
	(0.225)*	(0.275)**
Post-Entry*Colocation*Land	0.529	1.112
	(0.481)	(0.476)**
Post-Entry*Top NSF	-0.786	-0.723
	(0.371)**	(0.415)*
Post-Entry*Colocation*Top NSF	-2.111	-1.835
	(1.157)*	(1.139)
University FE	YES	YES
Year FE	YES	YES
Post-Entry*Region Dummy	YES	YES
Obs	6,181	6,181
Group	182	182
Log Likelihood	-1,433,517.90	-1,366,244.37

Notes: Poisson regression coefficients with QML robust standard errors clustered at the university level in parentheses. $^{*}p < 0.1$; $^{**}\ p < 0.05$; $^{***}\ p < 0.01$.

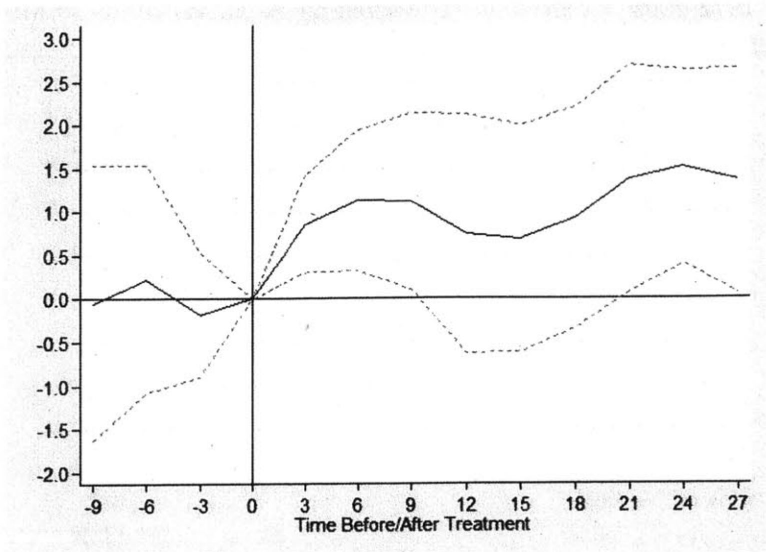
Table D.1: Placebo Regressions at the University Level

	(1) NSF Colocation Only	(2) NSF Full Model	(3) NIH Colocation Only	(4) NIH Full Model	(5) USDA Colocation Only	(6) USDA Full Model
Post-Entry*Colocation	0.201	0.225	0.17	0.334	0.065	-0.237
	(0.116)*	(0.268)	(0.084)**	(0.309)	(0.049)	(0.929)
Post-Entry*Early TTO		0.149		0.318		0.408
		(0.146)		(0.048)***		(0.230)*
Post-Entry*Colocation*Early TTO		-0.418		-0.389		-0.171
		(0.345)		(0.285)		(0.289)
Post-Entry*Medical		0.159		-0.116		0.197
		(0.102)		(0.106)		(0.105)*
Post-Entry*Colocation*Medical		-0.059		-0.03		-1.687
		(0.286)		(0.295)		(0.793)**
Post-Entry*Land		0.549		0.115		-1.403
		(0.126)***		(0.059)**		(0.286)***
Post-Entry*Colocation*Land		-0.247		-0.648		-0.384
		(0.200)		(0.244)***		(0.766)
Post-Entry*Top 25% NSF		-1.008		-0.076		-0.889
		(0.179)***		(0.217)		(0.592)
Post-Entry*Colocation*Top NSF		0.409		0.144		0.709
		(0.298)		(0.366)		(0.597)
University FE	YES	YES	YES	YES	YES	YES

Year FE	YES	YES	YES	YES	YES	YES
Post-Entry*Region Dummy	YES	YES	YES	YES	YES	YES
Obs	6,181	6,181	5,814	5,814	5,367	5,367
Group	182	182	182	182	182	182
Log Likelihood	-1,433,517.90	-1,366,244.37	-1,933,563.25	-1,879,529.73	-841,615.88	-811,645.85

Notes: Poisson regression coefficients with QML robust standard errors clustered at the university level in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Figure D.2: Yearly Treatment Effects (Colocation × Early-TTO)



Note: The blue solid line corresponds to the coefficient estimates from conditional fixed-effect quasi-maximum likelihood Poisson regressions in which the number of plant biotechnology publication is regressed upon the interaction terms between Colocation × Early-TTO and the number of years (binned in 3 year intervals) before/after treatment event (entry of colocated company's entry into plant biotechnology R&D). Year effects and the interaction terms between region dummy and 3-year indicators are included. Robust standard errors were clustered at the university level. The dashed red lines show the 95% confidence interval around these estimates.

Table D.3: Fixed Effect Poisson Regression of Plant Biotechnology Publications between 1972-2009, Colocation Redefined as Being Within a 30 Mile Radius

	(1) Colocation Only	(2) Colocation * Early TTO	(3) Colocation* Medical	(4) Colocation* Land
Post-Entry*Colocation	0.414	-0.554	-3.311	0.927
	(0.050)***	(0.327)*	(2.401)	(0.360)***
Post-Entry*Early TTO		-0.133		
		(0.037)****		
Post-Entry*Coloc.*Early TTO		0.917		
		(0.318)***		
Post-Entry*Medical			-3.701	
			(2.404)	
Post-Entry*Coloc.*Medical			4.687	
			(2.433)*	
Post-Entry*Land				-0.514
				(0.075)****
Post-Entry*Coloc.*Land				-0.549
				(0.345)
University FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Post-Entry*Region Dummy	YES	YES	YES	YES
Obs	3,344	3,344	3,344	3,344
Group	88	88	88	88
Log Likelihood	-3,465.34	-3,458.84	-3,453.22	-3,455.86

Notes: Poisson regression coefficients with QML robust standard errors clustered at the university level in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table D.4: Fixed Effect Poisson Regression of Plant Biotechnology Publications between 1972-2009, Colocation Redefined as Being Within a 60 Mile Radius

	(1) Colocation Only	(2) Colocation * Early TTO	(3) Colocation* Medical	(4) Colocation* Land	(5) Colocation* Top NSF	(6) Colocation* Full Model
Post-Entry*Colocation	-0.159	-0.564	-0.154	-0.004	0.400	0.867
	(0.274)	(0.212)***	(0.331)	(0.246)	(1.01)	(0.97)
Post-Entry*Early TTO		-0.237				-0.430
		(0.057)***				(0.097)***
Post-Entry*Colocation*Early TTO		0.872				1.417
		(0.233)***				(0.150)***
Post-Entry*Medical			0.037			0.177
			(0.084)			(0.016)***
Post-Entry*Colocation*Medical			0.172			-1.284
			(0.294)			(0.976)
Post-Entry*Land				-0.081		-0.298
				(0.096)		(0.088)***
Post-Entry*Colocation*Land				-0.182		-1.550
				(0.306)		(0.971)
Post-Entry*Top 25% NSF					-0.721	
					(0.221)***	
Post-Entry*Colocation*Top NSF					-0.567	
					(1.038)	
University FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES

Post-Entry*Region Dummy	YES	YES	YES	YES	YES	YES
Obs	3,876	3,876	3,876	3,876	3,876	3,876
Group	146	102	102	102	102	102
Log Likelihood	-3,976.17	-3,965.22	-3,975.41	-3,974.98	-3,973.09	-3,955.23

Notes: Poisson regression coefficients with QML robust standard errors clustered at the university level in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Chapter 2

Should we shoot for the stars?: Individual Antecedents of Reverse Knowledge Spillovers

2.1 Introduction

Due to the rapid rise of science-based industries during the past few decades, the contribution of academic research to industrial R&D and firm performance has become an extensively studied topic in the management literature during the past few decades. The existing literature has examined university-industry relationship from multiple different levels of analysis. Whereas a number of early empirical studies focus on the spillover effect of aggregate university R&D expenditure on industries at the sectoral level (Mansfield, 1995; Audretsch and Feldman, 1996; Jaffe, 1989), a significant body of research has subsequently been centered around university-company networks and alliances at the organizational level (Powell et al., 1996; Rothaermel and Deeds, 2004).

Another stream of research focuses on the role of *individual* academic scientists in the process of university-to-industry knowledge spillover and transfer (Audretsch and Stephan, 1996; Zucker et al., 1998; Bercovitz and Feldman, 2008). A plethora of empirical works examine how companies benefit from scientific knowledge produced by university researchers, especially "star scientists" in the right tail of the productivity distribution. They find that that being geographically co-located or contractually affiliated with star scientists have a positive impact on various industry outcomes such as valuable patents, firm founding and IPO success (Zucker et al., 1998, 2002; Fuller and Rothaermel, 2012; Higgins et al., 2011).

However, there exists an important caveat to the role of star scientists for the industry. A number of recent studies argue that productivity simply in terms of overall publication is not a sufficient condition for scientists' contribution to the industry, and that being under the Pasteur's quadrant (Stokes, 1997) – by pursuing both fundamental academic understanding as well as practical, real-world utility – is a necessary condition (Baba et al., 2009; Subramanian et al., 2013). The argument is that if knowledge produced by academic researchers has little application for potential uses in the relevant industry sector, it is unlikely to create significant spillover effect upon industry outcomes.

Many studies view patenting as a proxy of Pasteur bridging between academic science and industry technology. However, a fundamental prerequisite prior to academic patenting is whether a scientist pursues her research in industry-relevant fields of science. For example, bridging scientists for the plant biotechnology industry would include academic scientists that are highly productive in plant genetics and plant molecular biology, which industrial R&D heavily depends upon. Researchers in such industry-relevant fields, by definition, have a greater chance for patenting and other commercialization activities.

Although many empirical studies have tackled the question of what leads academics to patent their research, little attention has been given to what leads academics to conduct research in industry-relevant fields of science. Out of all subdisciplines in the broadly defined plant biology, which include less industry-relevant ones like fundamental cell biology or ecology of plants, why would certain researchers choose to engage in industry-relevant research in lieu of others? Addressing this gap in literature, I propose an analytical framework of academic knowledge production which argues the following: An academic's choice to research in industry-relevant fields of science is determined by the interplay of opportunities from the industry environment and the incentives of individual researchers in the university environment.

First, I discuss the types of opportunities created by the industry environment for academics to exploit. Following chapter 1, I use the term "reverse knowledge spillovers" to refer to the externalities created by these industry-driven opportunities upon the production of scientific knowledge in academia. Reverse knowledge spillovers are geographically localized, as academic researchers that are geographically proximate to a locus of industrial innovation will be able to tap into a greater flow of opportunities.

Second, I examine the individual antecedents that can shape academics' responses to reverse knowledge spillovers from the local industry. Academics' choices to respond to local industry opportunities will hinge upon their incentives, which are shaped by the institutional aspect of academic organizations that they are working for, as well as their individual career concerns. In this chapter, I particularly focus on the role of individual incentives which are determined by the opportunity cost of pursuing new industry-driven opportunities. I focus on two individual characteristics that may have a salient effect on researchers' responses to local industry shock: prominence and career age. I hypothesize that local industry R&D will disproportionately increase the industry-relevant research output of university researchers who have less prominence in academia and are early in their career, because their relative lack of research and resource opportunities within academia incentivizes them to seek out novel opportunities from the local industry.

I examine the hypotheses in the setting of the agricultural biotechnology industry, which experienced a radical change in the direction of industrial R&D in the 1980s. The agricultural biotechnology revolution and the subsequent change of industrial R&D at industry incumbent locations provided an exogenous shock to local universities colocated with the industry. I examine how academics that work at these industry-colocated universities respond to local industry shock, focusing on individual characteristics that may affect their opportunity cost of doing industry-relevant research.

Running individual fixed-effect Poisson regression on a sample of coarsened-exact-matched scientists, I find that incumbent scientists at colocated universities, whose Ph.D degrees are from less prominent academic institutions, experienced a positive and significant increase in plant-biotechnology-related publications after the rise of agricultural biotechnology industry in the region, compared to control scientists of similar career age and publication history. I also find that colocated individuals in early and late career are more responsive to the industry R&D effect, which implies that reverse spillover effect from the industry is particularly salient upon the "fringes" of academia. This provides new insight for firms' R&D strategy that engaging with the young and unestablished rookies in the local community and investing in their growth may be a strategic alternative to "reaching out for the (academic) stars".

2.2 Literature Review and Hypotheses

For a deeper understanding of the endogeneity of science to industrial innovation and technology, we need a systematic framework to make sense of these anecdotal examples. Building upon the literature on the economics and sociology of science, I depict the trajectory of scientific knowledge production as a function of two main inputs, opportunities and incentives. The production of scientific knowledge proceeds through three stages: the creation of opportunities, the access to opportunities and the filtering of opportunities through incentives. This framework is graphically depicted in Figure 2-1.

Insert Figure 1 about here

2.2.1 Creation of Opportunities for Scientific Knowledge Production

Production of science is a costly process that requires both cognitive and physical input, and the availability of such inputs within a certain field of science not only determines research productivity within the field but also the entry of researchers into the field. The literature allows us to identify four types of opportunities for scientists to gain cognitive and physical resources, which serve as a crucial input to scientific knowledge production: knowledge opportunities, resource opportunities, professional opportunities and entrepreneurial opportunities. In this section, I briefly outline how industry creates new opportunities for academics in each of these aspects.

Knowledge Opportunities

Technological innovations in the industry can provide academic scientists with new knowledge opportunities to identify new phenomena and establish novel hypotheses that will challenge existing scientific beliefs (Evans, 2010; Rosenberg, 1982). For example, Bell Lab's breakthrough discovery of the transistor effect initiated a subsequent commitment of scientific efforts to understand the physics behind it, and this led to a rapid growth of solid state physics in academia. Knowledge opportunities also arise as a result of new instruments and laboratory techniques that facilitate the process and expand the scope of scientific discoveries. Invention of the polymerase chain reaction technique by the Cetus Corp vastly advanced the life sciences field including genetics, pathology, and many other disciplines.

Resource Opportunities

Faced with an increasing need for sophisticated equipment and a greater competitive pressure for funding, the influx of resources from the industry, such as research funding and scientific materials, may motivate academic scientists to branch out their research in a direction which they can potentially benefit from exploiting the resources in the industry. Empirical studies have shown that the availability of funding can vastly expedite the growth of a scientific field by increasing the entry of scientists into the field, as well as the productivity of scientists already in the field (Freeman, 1975; Jacob and Lefgren, 2011).

Professional Opportunities

With the increasing size of Ph.D classes and the declining growth of resources in higher education, the job demand for academic scientists also often fails to meet the supply of candidates and we see an increasing duration in postdoc training across many disciplines as well as academic scientists' transition into non-academic positions (Sauermann and Roach, 2012; Stephan and Ma, 2005). Because an industry career is also a viable exit option for academic scientists, a relative decrease in federal funding combined with an increase in industrial R&D may encourage the entry of risk-averse academic scientists into the industry-relevant field.

Entrepreneurial Opportunities

Entrepreneurial opportunities, which enable researchers to capitalize their research findings through patenting and firm founding, also have a significant effect upon the trajectory of scientific research. As noted in Stokes (1997), potential downstream commercial benefits and entrepreneurial returns from scientific research can be a source of motivation for scientists. With the recent institutional changes that have enabled universities and academics to appropriate monetary returns from their scientific research through patenting and firm founding, such as the Bayh-Dole Act and Diamond v. Chakrabarty Case, entrepreneurial opportunities have been embraced as an increasingly important element for scientists in setting their path of scientific research (Murray, 2010; Owen-Smith, 2003). For example, Azoulay et al. (2009) provide empirical evidence that the opportunity to patent one's research can shift the direction of academic research further towards more patentable research.

2.2.2 Access to Opportunities: Geographical Localization of "Reverse Knowledge Spillovers"

As mentioned above, industry presence can create significant externalities upon the production of academic science by being a consumer of or collaborator with university research, supporting the formation of market for ideas and thickening the labor market. I call such externalities "reverse knowledge spillovers" to distinguish it from the traditionally studied knowledge spillovers from academia to industry.

Proximity between academic researchers and industry innovators can shape the extent of reverse knowledge spillovers. Although there are multiple dimensions to the concept of proximity, I focus on the role of geographical proximity between universities and industry in the context of my study. The argument is that, for example, academics in Silicon Valley have a greater access to knowledge, resources, and professional and entrepreneurial opportunities in the IT industry-related fields of science, compared to equally competent scholars in the Midwest, by the virtue of being colocated with IT firms.

Reverse knowledge spillovers are geographically localized for a number of reasons. Industry may have a preference for local academic partners for contract research and joint collaboration because geographical proximity lowers coordination, monitoring and communication costs (Kraut et al., 1988). They may be motivated by the fact that the lower opportunity cost of traveling over shorter distance can lead to more novel experimentation and recombinations of ideas (Catalini, 2012). Firms can also assist academic research by sharing valuable resources like expensive machinery or rare stem cell lines (Evans, 2010), and such relationships may be strengthened by reciprocal trust and social bond that reside in the local region (Saxenian, 1996)).

Academics may also develop a greater alignment of their research with local industry, because their social embeddedness within the regional community induces them to identify and exploit professional or entrepreneurial opportunities within geographical proximity. Although the labor market for science and engineering operates at a national scale in the long run, the embeddedness of people in the local labor and social networks limits the effective scope of the labor market in a shorter period to the regional level (Almeida and Kogut, 1999; Kerr and Lincoln, 2010; Topa, 2001). Professional and entrepreneurial opportunities can induce potential boundary-spanners in academia to align their research with local industry, so that if they were to leave academia, they can more easily find a job or start a company in the local labor market, as they can better leverage their social ties to mobilize important information and resources when they reside closer to those resources (Stuart and Sorenson, 2003).

In summary, as a result of more frequent interactions between geographically proximate companies and universities, academics will have a greater access to industry-driven opportunities in the regional innovation system, and we will thus observe geographical localization of reverse knowledge spillovers.

2.2.3 Filtering of the Opportunities: The Role of Organizational & Individual Incentives

Geographical proximity to industrial opportunities is a necessary but not sufficient condition for reverse knowledge spillovers. Scientific knowledge production is a function not merely of opportunities, but also of a set of incentive structures and institutional mechanisms that shape and constrain behavioral choices of scientists by filtering the opportunities.

Organizational Incentives

As defined in Chapter 1, I use the term "boundary-spanning capacity" to encompass an organization's institutional infrastructure and norms which facilitate and incentivize academic scientists to exploit industry-driven opportunities by spanning the industry boundary.

The boundary-spanning capacity of universities works bi-directionally, both incentivizing academic researchers to pursue industry-relevant science and simultaneously inducing industry to invest in the university. An academic's decision to delve into industry-relevant research is not merely determined by the amount of potential pecuniary payoff, but also by whether the university has the institutional capacity to support and incentivize that decision. Concurrently, the industry's decision to fund and sponsor universities is not simply determined by whether universities have the best-quality researchers, but also by whether universities have the institutional capacity to enable industry to reap the returns to investments in an efficient manner. Unless a university has an institutional capacity to support and foster industry interactions, its researchers will not be incentivized to take advantage of the opportunities that local industry may provide, or local industry, recognizing the university's lack of capacity, will not offer any such opportunities. I therefore make the following prediction:

> Hypothesis 1: Industrial R&D in an academic's geographical proximity ("local industrial R&D") has a greater positive effect upon the individual's research in industry-relevant fields of science, if the academic's university has strong boundary-spanning capacity.

Individual Incentives

In addition to the set of organizational incentives, the individual response to opportunities arising from the local industry is also moderated by individual-specific incentives. I propose that the degree to which scientists will be incentivized to exploit new knowledge and resources opportunities from the industry depends upon the scarcity of the individual's existing opportunities and the strength of path-dependency in his or her existing research trajectory.

One argument from the supply-side perspective of academics is that established scientists of higher prominence in academia have a weaker incentive to seek outside of academia for external research opportunities and resources, as they are likely to have secured more federal research grants and extensive academic collaborating network. In contrast, scientists with less academic reputation, due to their lack of outside funding options, have a stronger incentive to accept external funding sources that are more applied and sponsor-oriented (Goldfarb, 2008). Also, because prominent academics are likely to be more heavily invested in a pre-existing research trajectory, path-dependency can also demotivate them from being attentive to new opportunities arising from industry.

Another argument coming from the demand-side perspective is that less prominent scientists are incentivized to focus on opportunities in the local environment because their opportunity set is more geographically bounded. Existing literature suggests that a scientist may collaborate with another scientist, and a company may collaborate or invest in a scientist, not just for practical research purposes but also to build on the scientist's reputational benefits to signal scientific quality and credibility to the audience (Audretsch and Stephan, 1996; Simcoe and Waguespack, 2010). While prominent scientists offer reputational benefits which will outweigh the collaboration costs incurred by geographical distance, less prominent ones will be disadvantaged in their ability to create reputational spillovers and thus seem less attractive to geographically distant ties. Younger and less prominent scientists have less visibility in the academic network, which raises the barrier to finding potential collaborators and resource providers across geographical distance.

In short, the opportunity set of younger, less prominent scientists is not only smaller in terms of volume, but also more geographically bounded. As a result, they have an incentive to align their direction of research with the opportunities present in the local environment. Thus, I hypothesize the following;

> Hypothesis 2: Industrial R&D in an academic's geographical proximity ("local industrial R&D") has a greater positive effect upon the individual's research in industry-relevant fields of science, if the individual is younger in career age.
>
> Hypothesis 3: Industrial R&D in an academic's geographical proximity ("local industrial R&D") has a greater positive effect upon the individual's research in industry-relevant fields of science, if the individual is less prominent.

2.3 Research Setting and Design

2.3.1 Identification Strategy

In order to measure the impact of local industrial R&D upon the rate and direction of academic science, I use a difference-in-difference estimation strategy which compares the change in industry-colocated academics' research output to the changes of a comparable group that are not colocated with industry R&D. In order to make sure that both treated universities and academics are compared to a valid group of counterfactuals, I employ coarsened-exact-matching on a number of observable characteristics as well as the pre-treatment outcome.

As explained in Chapter 1, industrial R&D in agricultural biotechnology is dominated by a very small number of incumbent companies called the "Big 6" (Monsanto, DuPont, Syngenta, Dow Agrosciences, Bayer, BASF), which originally started in non-biotechnology agribusinesses such as seed breeding, agrochemicals and animal health. Because of a greater focus upon in-house R&D (rather than external sourcing) combined with locational inertia of agricultural R&D, these companies did not relocate their R&D activities despite their transition to new areas of R&D and the increasing dependence upon academic science.

Looking into the history of the Big 6, I identify Monsanto, Du Pont, Pioneer Hi-Bred, Ciba Geigy, and Elanco as the major anchor tenants in non-biotechnology agribusiness that made the transition to become one of the Big 6 in agricultural biotechnology R&D. Monsanto's agricultural biotechnology R&D has been concentrated in its R&D headquarters in St. Louis, Missouri, where they initially started as an agrochemicals company in 1901. DuPont's agricultural biotechnology R&D is concentrated in the DuPont Experimental Station in Delaware and Pioneer Hi-Bred Headquarters in Johnston, Iowa, a major seed company that they acquired in the late 1990s. Syngenta has been located in Research Triangle Park, North Carolina, near where its mother company Ciba Geigy had operated its agrochemicals division since the early 1970s. Bayer and BASF's agricultural biotechnology division also enter into

Research Triangle Park later in the 1990s. Dow Agrosciences has been located in Indianapolis, Indiana, since the mother company of its predecessor Dow Elanco, Eli Lilly, had operated an agrochemicals division (originally named Elanco) in Indianapolis.

At the individual level, an academic can be considered to have been treated by colocation with industrial R&D in two cases: incumbents and entrants. In the case of an incumbent individual who was already been present at a university that has been colocated with a company since before the company's entry into plant biotechnology R&D, the individual is considered to have been treated in the years after the company's new R&D entry. When an individual researcher is recruited into a treated university after the company's entry into plant biotechnology R&D, the individual is considered to have been treated after the individual's move into the treated university.

Whereas universities are fixed in place, individual researchers move in and out of industry-colocated locations depending upon the individual taste for industry-relevant research. In the case of entrants moving into treated universities after the rise of local industrial R&D, the industry effect will capture both the treatment effect of industry R&D on the entrants and the selection effect caused by non-random entry of researchers into those locations. In case of incumbents already at industry-colocated universities at the time of treatment, the industry effect will capture the treatment effect of local industry R&D on the incumbents, plus possible selection effect if the incumbents selected into those universities in anticipation of the local industry entering into plant biotechnology R&D.

In order to alleviate the selection effect, I also used the coarsened exact matching approach to compare both entrants and incumbents at treated universities against a group of scientists that have comparable pre-treatment publication history and taste for plant biotechnology research. I conducted matching on 1) the career entry year, 2) the cumulative number of plant biotechnology publications, and 3) the cumulative number of entire publications. The crucial identification assumption for the individual-level analysis is that coarsened exact matching on the pre-treatment publication history provides valid counterfactuals for treated individuals.

2.3.2 Procedure of Coarsened-Exact-Matching

At the individual level, the controls were chosen based upon the following set of covariates: the career entry year (binned at 1940, 1943, 1945, 1947, 1950 ... 2005 and 2007), as well as the stock of overall publications (at 25th, 50th, 75th, 90th, 95th and 99th percentile) and plant biotechnology publications (at 25th, 50th, 75th, 90th, 95th and 99th percentile) up to the year of treatment (colocation with industry R&D). I coarsened the joint distribution of the covariates by breaking the continuous variables into separate bins (cut-off values at 25th, 50th, 75th, 90th, 95th and 99th percentile) and keeping the strata that contained one treated university and at least one control. I implement 1-to-1 CEM procedure before each treatment year without replacement, trimming the number of observations from 607 to 306 scientists.

2.3.3 Econometric Specification

The main empirical strategy of this study is difference-in-difference estimation. The impact of industry R&D on the treated universities and individuals will be compared against controls which are comparable on observable characteristics. I identify the controls by using coarsened exact matching (Iacus et al., 2012), an empirical approach which remedies the endogeneity of treatment variable by balancing the treated and control observations on exogenous variables.

The unit of analysis is scientist-year. The econometric specification at the individual level is a difference-in-differences estimation with varying treatment intensity for different types of individuals. The outcome variable of interest is individual scientist j's publication outcome in time t.

The main treatment variable is $Post-Colocation_{i,j,t}$ which equals 1 for individual scientist j who works at an industry-colocated university i at time t, only after the year in which the university i was "treated" by colocated company's entry into plant biotechnology R&D. $Incumbent_{j,t}$ equals 1 for scientist j who is present at a "treated" university at time t, if the scientist had been working at the university since at least 3 years before the treatment. $Entrant_j$ equals 1 for scientist j who is present at a "treated" university at time t, if the scientist entered the treated university not before 3 years prior to the treatment.

I control for individual fixed effect, year effect, a vector of university-level controls X_i, as well as a suite of indicator variables to control individual j's tenure at time t. In short, the coefficient δ estimates the impact of industry R&D colocation upon incumbent scientists at treated universities, whereas the coefficient ρ estimates the impact of industry R&D colocation upon entering scientists at treated universities. The treatment effect is moderated by the status variable W_j, which is a vector of indicator variables that are used to denote a scientist's prominence and career age.

$$
\begin{aligned}
Publication_{i,j,t} = f(\epsilon_{i,j,t}; \alpha_j + \beta_t + \gamma X_i + \eta Tenure_{j,t} + \delta Post\text{-}Colocation_{i,j,t} \\
\times Incumbent_{j,t} \times W_j + \rho Post\text{-}Colocation_{i,j,t} \times Entrant_{j,t} \times W_{j,t})
\end{aligned}
$$

As the dependent variable is a nonnegative count variable with skewed distribution, I use the conditional fixed-effect Poisson model with QML (quasi-maximum-likelihood) standard errors clustered at the individual level. According to Wooldridge (1997), QM L("robust") standard errors are robust to the issues of serial correlation raised by Bertrand et al. (2004).

2.4 Data and Variables

2.4.1 Sample

To identify the sample of academic scientists in plant-biotechnology-related disciplines, I use the membership directory of American Society of Plant Biologists. Although this directory does not cover the entire population of scientists who have ever published in plant-biotechnology-related fields (especially those who had only been active in the early years of the industry), the left truncation is not particularly severe as the rise of plant biotechnology is relatively a recent phenomenon. After dropping scientists that only worked at non-U.S. institutions, only worked in non-academic positions, or cannot be identified in the Web of Science, I have a sample of 607 scientists. I used their publication records and CVs to construct their career histories. The coarsened exact matching brings the sample down to 306 (a matching rate of about 50%).

2.4.2 Variables[1]

Dependent Variables

Publication output in plant-biotechnology related sciences. The dependent variable of interest is the university's (or the individual's) publication output that is relevant to industrial R&D in plant biotechnology. The easiest way to collect the data for this dependent variable is to gather all publications in journals that specifically focus on plant biotechnology. However, this comes at a cost of missing relevant articles that are published in journals of a broader discipline, such as Plant Physiology and the Journal of Biological Chemistry. In order to gather all relevant articles regardless of the journal's disciplinary orientation, I use the following two-step procedure: I first downloaded titles and abstracts from the top three journals in the field of plant molecular biology and genetics: Plant Cell, Plant Molecular Biology and Plant Biotechnology Journal. By using a text-mining process[2], I extracted a set of essential keywords that are relevant to sciences of plant biotechnology and repeatedly appear in these articles. Then I applied the combination of these keywords to search Web of Science to download all publications which contain the keywords in their title or abstract. I identified the author addresses in these articles to aggregate them at the university level.

[1]Some of the text in this section is taken from Chapter 1, which uses the same research setting.
[2]I used the online text-mining tool called TerMine, available at http://www.nactem.ac.uk/software/termine/.

Explanatory Variables

Colocation with Industry R&D (university-level). As mentioned in the previous section, I identified the loci of treatment as the following five locations: Monsanto Headquarters in Creve Coeur, Missouri; Du Pont Experimental Station in Wilmington, Delaware; Ciba Geigy (now Syngenta)'s Agricultural Biotechnology Research Center in Research Triangle Park, North Carolina; Pioneer Hi-Bred (now part of Du Pont) Headquarters in Johnston, Iowa; DowElanco (now Dow Agrosciences) Headquarters in Indianapolis, Indiana. I identified the exact location of the main R&D laboratory by cross-checking the Directory of American Research and Technology and the author addresses in company publications.

I considered universities within a 100-mile radius of these locations as geographically proximate to a locus of industrial R&D (*i.e.* colocated with the company), as suggested in Furman and MacGarvie (2009). The treatment is considered to have taken place when the colocated company entered into plant biotechnology R&D by launching an official internal unit or a joint venture dedicated to plant biotechnology (*e.g.* Monsanto in 1981, Ciba Geigy in 1984, Pioneer in 1989, DowElanco in 1989). In the case of Du Pont, I could not date the official launching of a plant biotechnology team from official sources, although it is known that it entered the industry around the same time as Monsanto. Instead, I take 1982, when Du Pont first published an academic paper in the topic of plant molecular genetics, as the treatment year.

Colocation with Industry R&D (researcher-level). An academic researcher is considered to be colocated with industry R&D in a year in which he or she is present at a university colocated within a 100-mile radius from the anchor tenants. I distinguish two types of industry-colocated researchers: incumbents and entrants. Incumbent researcher refers to an individual who had been present at the colocated universities since at least 3 years before the anchor tenant's entry into plant biotechnology R&D. Entrant researcher refers to an individual who gets recruited into the colocated universities in the years after the industry shock. For example, Monsanto entered into plant biotechnology R&D in 1982. Roger Beachy, a researcher at Washington University in St. Louis, is considered to be an incumbent because he had been present at the university since 1978. On the other hand, David Tuan-hua Ho, another researcher at Washington University is considered to be an entrant because he had been present at the university since 1984.

Strength of University's Boundary-spanning Capacity. My hypothesis states that the impact of industry R&D will affect a colocated university when its researchers have access to boundary-spanning institutions that facilitate and incentivize university-academia interactions. I use several proxy measures for the strength of a university's boundary-spanning capacity: (1) the existence of a technology transfer office (TTO) before 1980, (2) the existence of a medical school at the university, and (3) the land-grant status of the university.

The fact that a university had an active TTO before 1980, even prior to the enactment of the Bayh-Dole Act which opened the era of academic patenting, suggests that the university has had an exceptionally strong culture and infrastructure that supported research commercialization. Such universities are likely to have had high experience in technology transfer services and industry collaboration, which will further facilitate and incentivize boundary spanning by academic scientists into industry. Having a medical school also has a similar implication, in that it is the earliest form of institutional innovation that incentivized practical, applied and technological research even before the advent of biotechnology (Rosenberg, 2009). Land-grant status counts as a proxy of boundary-spanning capacity in this particular industry context because land-grant status had been given with the mission to focus on practical agriculture and engineering.

These institutional features suggest that a university had early exposure to technology transfer and industry collaboration and is likely to have built a more systematic infrastructure to further aid subsequent industry boundary-spanning. Thus, the universities with higher initial boundary-spanning capacity are likely to exhibit subsequent development of boundary-spanning capacity and a faster shift into industry-relevant research compared to their counterparts.

Individual Career Status. To test the second hypothesis that the impact of industry R&D is higher upon colocated scientists of less prominence and younger career age, I examine the following: (1) whether the individual has a Ph.D from one of the top 25 academic institutions in terms of NSF funding and (2) the number of years since the year of Ph.D degree (or the year of first publication if the former is unavailable). Previous research has noted that the departmental prestige of an academic's Ph.D degree is the basis of cumulative advantage, which allows them to gain differential access to resources and rewards that enhance their subsequent career in the long run (Burris, 2004; Bedeian et al., 2010). The top 25 Ph.D granting institution is determined by ranking them in terms of average NSF funding prior to 1980.

Control Variables

I collected university-level data from the NSF Survey of Research and Development Expenditures at Universities and Colleges, as well as the NSF Survey of NSF Survey of Graduate Students and Postdoctorates in Science and Engineering. I used a set of university-level variables to match control universities to the set of treated universities (the procedure of matching is explained in the Appendix C). I include university-level controls and career age indicator variables (binned in 10 year intervals) in university-level fixed-effect regressions. Regional shocks may also affect the evolution of agricultural biotechnology research. For example, the Midwest or the Southeastern region have a natural advantage for important commercial crops such as maize, soybean and cotton, and the federal and state governments may provide disproportionate funding and incentives for universities in these regions. In order to control for such region-specific shocks, I include region-year interactions in the university level regressions and regional indicator variables in the individual level regressions.[3]

[3]NSF survey categorizes university location into 9 regions (1: East North Central/Great Lakes Region (Illinois, Indiana, Michigan, Ohio, Wisconsin), 2: East South Central Region (Alabama, Kansas, Mississippi, Tennessee), 3: Middle Atlantic Region (New York, New Jersey, Pennsylvania), 4: Mountain Region (Arizona, Colorado, Indiana, Montana, New Mexico, Nevada, Utah, Wyoming), 5: New England Region (Connecticut, Massachusetts, Maine, New Hampshire, Rhode Island, Vermont), 6: Pacific Region (California, Hawaii, Oregon, Washington), 7: South Atlantic Region (DC,

2.5 Results and Analysis

2.5.1 Descriptive Statistics

The descriptive statistics of 306 individuals in my final sample are presented in 2.1. Table 2.1 confirms that my CEM (coarsened exact matching) procedure resulted in a balanced match of treated and control individuals, so that there is no significant difference between the sample moments of the two groups. Matching on the R&D expenditure funded by public sources (NSF and USDA), student body, land grant status and the existence of an agricultural sciences and genetics department have also achieved a balance across other observable covariates that were not included in the matching criteria.

Insert Table 2.1

2.5.2 Main Result

Table 2.3 and Table 2.4 look at how the impact of local industry R&D upon individual researchers' plant biotechnology publication outcome differs by the prominence of doctoral degree and career age. Fixed effect Poisson regression estimates are reported, and all models include researcher-level fixed effects, as well as year effects (binned in 5 year intervals), region dummies and tenure dummies (binned in 10 year intervals). Robust standard errors are clustered at the researcher level.

Model 1 of Table 2.3 shows that the anchor tenants' entry into agricultural biotechnology R&D had a positive and significant impact only upon colocated incumbent researchers of less prominent doctoral degree, as predicted by Hypothesis 2. Compared to non-colocated researchers with similar career history, the plant biotechnology

Delaware, Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia), 8: West North Central/Plains Region (Iowa, Kansas, Minnesota, Missouri and Nebraska) and 9: West South Central Region(Arkansas, Louisiana, Oklahoma, Texas)). I interact these variables with the Post-Entry indicator and include the interaction terms in the regressions.

publication of colocated incumbent scientists received an increase of 416%. As shown in Model 2, the local industry effect is also positive and significant, albeit of smaller magnitude, if we weight the publication outcome by normalized citations. Researchers that entered the industry location after the official launch of plant biotechnology R&D did not experience a significant increase in plant biotechnology publication output. Model 3 of Table 2.4 presents a placebo regression run with the dependent variable being the publication outcome in non-biotechnology-related fields (which is equal to the total number of publications minus the number of plant biotechnology publications).. The placebo regression confirms that the local industry R&D effect has not been driven by the general productivity increase of researchers at treated universities.

The coefficient on *Post-Colocation* $*$ *Incumbent* captures the impact of anchor tenants' entry into agricultural biotechnology R&D upon incumbent researchers who had been present at the colocated universities for at least 3 years before the entry. On the other hand, the coefficient on *Post-Colocation* $*$ *Entrants* captures the impact of industry colocation upon newly recruited "entrant" researchers who enter into colocated universities no earlier than 2 years before the anchor tenants' entry into plant biotechnology R&D. Although I coarsened-exact-match both sets of researchers to non-colocated researchers in terms of their pre-treatment publication history, I focus on the coefficient on *Post-Colocation*$*$*Incumbent* because *Post-Colocation*$*$*Entrant* is likely to be confounded with unobservable selection bias.

Insert Table 2.3 about here

Table 2.4 shows how academic researchers' career age at the time of treatment can moderate the impact of industry R&D upon colocated researchers. The regression results in Model 1 and 2 show that industry-colocated incumbent researchers that are in either early or late career age experience a positive and significant increase in plant biotechnology research after the rise of agricultural biotechnology industry compared to their controls. The finding that incumbent scientists in late career also experience a relative increase in industry-relevant research output is unexpected, but this may be due to the fact that they have less active projects and more freedom compared to mid-career scientists and thus be more attentive to local opportunities. On the other hand, industry-colocated incumbent researchers in the middle of their career (at the time of treatment) do not experience a significant increase in plant biotechnology-related research. Model 3 looks at the impact of local industry R&D on non-plant biotechnology publication outcome, which is defined as an individual's publications after netting out plant biotechnology publications. An interesting fact is that younger scientists in the treated regions subsequently face a relative decline in non-plant biotechnology publications, which implies that their productivity gain in plant biotechnology research may come at a cost of sacrificing other future research streams.

Insert Table 2.4 about here

2.6 Discussion and Conclusion

A major weakness in the university-industry knowledge spillovers literature is that most studies have abstracted away from the microfoundations behind individual choices to get involved in the endogenous process of local industry-relevant research. Prior discussions have focused primarily on how academics respond to macro-level changes in public policy and economic incentives brought by the industry, without delving into local-level interactions and mechanisms that mediate the convergence between industry R&D and academic research.

This study contributes to the body of research on university-industry relations by highlighting the "who, where and why" of industry-driven change in academic science. I provide empirical evidence for my argument that reverse knowledge spillovers from industry have a greater influence among a select group of academics that have stronger individual incentives to respond to local industry opportunities. The results from the individual fixed-effect regressions confirm the hypotheses that less prominent and younger academics, subject to the lack of alternatives and less opportunity cost incurred by engaging in industry-relevant research (thus a stronger incentive to exploit local industry opportunities), experience greater productivity boost in local industry-relevant fields of science. The results are consistent with the theory of knowledge spillover strategic entrepreneurship (Agarwal et al., 2007), which argues that knowledge spillovers are endogenously created by the strategic investments of incumbent firms and proliferated by the deliberate choice of (potentially entrepreneurial) individuals to act on those opportunities.

For corporate managers, the findings imply that relocation of R&D activity for scientific talent, recruitment of academic stars into the region or long-distance collaboration may not be the only option to attain the necessary scientific knowledge, as local talent may be cultivated through purposeful investment. The finding that local scientists of less prominent background and younger tenure exhibit a stronger increase in industry-relevant science output specifically highlights the role of non-star scientists who have received less attention in prior literature. For locally-based companies that have pre-existing networks in the regional community, identifying high-potential, young scientists in the local scientific community may bring a good return on investment in the long run.

Interpreting the findings from the resource-based view of the firm (Dierickx and Cool, 1989; Peteraf, 1993) provides new strategic imperatives for R&D investment and human resource management. Uncertainty in the future value of young and less established researchers and their up-side potential (in terms of industry-relevant research output) means that they provide better ex-ante limits to competition compared to academic stars whose market value is widely appreciated and thus function as a source of competitive advantage. Also given that researchers follow a path-dependent research trajectory, investing early in young researchers and locking their trajectory into industry-relevant or firm-specific direction provides ex-post limits to competition against other industries or firms that vie for academic human capital in the labor market. Thus firms may benefit from employing a "real option" perspective in investing academic human capital, engage in multiple early-stage investments in young academics and select on potential future stars in the right tail. This will be especially effective for established firms that are entering into new areas of R&D, which need not depend upon star scientists' reputation for survival.

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Figure 2-1: Framework of Endogenous Science

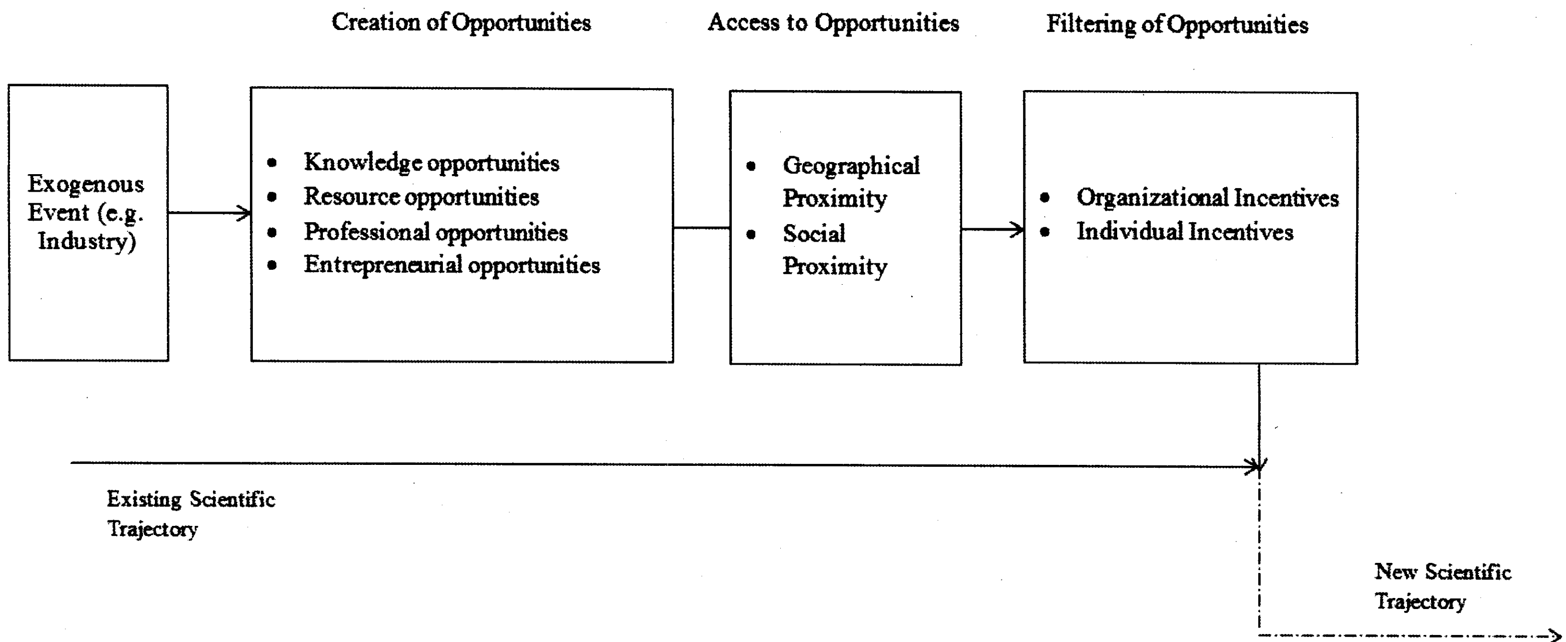

Table 2.1: T-Test of Treated Individuals and Control Individuals' Pre-Treatment Characteristics

	Treated Individuals	Control Individuals	Difference	T-stat (P-value)
Pub Count (Flow)	1.69(0.05)	1.63(0.05)	0.06(0.08)	0.79(0.43)
Plant Bio Pub (Flow)	0.19(0.02)	0.19(0.02)	0.00(0.02)	-0.12(0.91)
Non-Plant Bio Pub (Flow)	1.50(0.05)	1.44(0.05)	0.06(0.07)	0.77(0.44)
Career Age	7.43(0.19)	7.43(0.19)	0.01(0.27)	0.02(0.98)
Top 25 Ph.D	0.36(0.01)	0.37(0.01)	-0.01(0.02)	-0.5(0.616)
Ph.D Year	1977.38(0.47)	1977.32(0.55)	-0.06(0.70)	-0.10(0.923)
	153 individuals	153 individuals		

Table 2.2: Fixed Effect Poisson Regressions of Researcher Publication Outcome by the Prestige of Ph.D Institution

	(1) Plant Biotech Publications	(2) Citation-normalized Plant Biotech Publications	(3) Non-Plant Biotech Publications
Post-Coloc.*Incumbent Non-Early TTO	0.494 (0.593)	-0.340 (0.625)	-0.001 (0.148)
Post-Coloc.*Incumbent Early TTO	1.422 (0.385)***	0.987 (0.489)*	0.096 (0.168)
Post-Coloc.*Entrant* Non-Early TTO	-0.203 (0.201)	0.311 (0.273)	-0.007 (0.145)
Post-Coloc.*Entrant Early TTO	0.263 (0.176)	0.002 (0.366)	0.128 (0.136)
Individual FE	YES	YES	YES
Region FE	YES	YES	YES
Tenure FE	YES	YES	YES
Year FE	YES	YES	YES
Obs	4,105	4,105	4,105
Group	240	240	276
Log Likelihood	-3,611.49	-4,900.84	-6,296.15

Notes: Poisson regression coefficients with QML robust standard errors clustered at the individual level in parentheses. $*p < 0.1$; $**\ p < 0.05$; $***\ p < 0.01$.

Table 2.3: Fixed Effect Poisson Regressions of Researcher Publication Outcome by the Prestige of Ph.D Institution

	(1) Plant Biotech Publications	(2) Citation-normalized Plant Biotech Publications	(3) Non-Plant Biotech Publications
Post-Coloc.*Incumbent Top 25 Ph.D	-0.096	-0.330	0.267
	(0.432)	(0.379)	(0.202)
Post-Coloc.*Incumbent Not Top Ph.D	1.645	1.582	-0.155
	(0.362)***	(0.484)***	(0.115)
Post-Coloc.*Entrant* Top 25 Ph.D	-0.247	-0.099	0.074
	(0.188)	(0.302)	(0.192)
Post-Coloc.*Entrant Not Top Ph.D	0.181	0.162	0.195
	(0.180)	(0.282)	(0.180)
Individual FE	YES	YES	YES
Region FE	YES	YES	YES
Tenure FE	YES	YES	YES
Year FE	YES	YES	YES
Obs	4,204	4,204	4,204
Group	245	245	290
Log Likelihood	-3,800.65	-5,039.93	-6,547.88

Notes: Poisson regression coefficients with QML robust standard errors clustered at the individual level in parentheses. $*p < 0.1$; $** \ p < 0.05$; $*** \ p < 0.01$.

Table 2.4: Fixed Effect Poisson Regressions of Researcher Publication Outcome by Career Age

	(1) Plant Biotech Publications	(2) Citation-normalized Plant Biotech Publications	(3) Non-Plant Biotech Publications
Post-Coloc.*Entrant* Early Career	0.335 (0.298)	0.350 (0.398)	0.271 (0.170)
Post-Coloc.*Entrant* Mid Career	-0.063 (0.329)	0.105 (0.484)	0.003 (0.214)
Post-Coloc.*Entrant* Late Career	0.628 (0.443)	-0.133 (0.539)	-0.926 (1.108)
Post-Coloc.*Incumbent* Early Career	1.024 (0.558)*	1.149 (0.517)**	-0.318 (0.147)**
Post-Coloc.*Incumbent* Mid Career	1.033 (0.669)	0.592 (0.657)	0.060 (0.116)
Post-Coloc.*Incumbent* Late Career	1.340 (0.285)***	1.037 (0.259)***	0.131 (0.251)
Individual FE	YES	YES	YES
Region FE	YES	YES	YES
Tenure FE	YES	YES	YES
Year FE	YES	YES	YES
Obs	4,140	4,140	4,685
Group	239	239	279
Log Likelihood	-3,684.42	-4,823.32	-6,450.39

Notes: Poisson regression coefficients with QML robust standard errors clustered at the individual level in parentheses. *$p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Chapter 3

The Endogeneity of Science*

3.1 Introduction

The impact of Science on technological change and economic growth has long been at the cornerstone of the economics of science and science policy. Building on the seminal insights of Nelson (1959) and Arrow (1962), economists have recognized that certain types of knowledge – particularly the types of abstract knowledge which have historically been associated with scientific disciplines – may suffer from a severe appropriability problem. The production and use of scientific knowledge is hard to monitor and subject to expropriation, and the level of production may be inefficiently low in the absence of governing institutions. Given the centrality of knowledge spillovers and cumulative knowledge production in economic growth (as emphasized by, among others, Romer (1986) and Romer (1990)), the potential for significant inefficiencies in the production and diffusion of scientific knowledge has spurred intense interest by economists in how scientific research is funded and organized.

Researchers have argued that the Open Science regime, based on priority, disclosure and public funding, is the social solution to the appropriability and underinvestment problem involved in the production of scientific knowledge (Dasgupta and David, 1994). Academic institutions, financially supported by the government and free from contractual restrictions on the disclosure and diffusion of knowledge, are

*This work is joint with Scott Stern and Nate Rosenberg.

regarded to be the centers of the Open Science regime. Academics, governed by the internal norms and incentives of academia, contribute to the progress of science by freely pursuing their research interests. Instead of seeking practical applications of knowledge to solve a limited set of specific technical problems, academics pursue broad and general understanding about the laws of nature, which is thus called basic research. This notion of *exogenous* science – science progressing according to its own logic that is independent of other economic forces in the innovation system – has often underlaid the rhetoric of the "linear model", which emphasizes the autonomous work of academic researchers and their basic science research ouput as the key driver of technological innovation and economic growth.

While the economics of science and most public policy discussions initially focused on the so-called "linear" model, a significant body of subsequent research in economics and related disciplines has challenged the basic premise of the linear model, calling attention to science as an *endogenous* outcome, *i.e.* as a variable that are responsive to economic forces in the innovation system. The core argument in this stream of research has been that science progresses as a result of non-linear and interactive feedback loops between different innovative actors in the economy at different stages of the innovative process (Rosenberg, 1982; Kline and Rosenberg, 1986; Rosenberg and Nelson, 1994; Murmann, 2013a). The first goal of this essay is to draw out some of the crucial pathways and feedback mechanisms by which the structure, conduct and performance of the scientific research enterprise become responsive – *i.e.*, endogenous – to the institutional environment, technology and economic objectives.

However, as Balconi et al. (2010) have put it, understanding science as an endogenous outcome of the economy should not be confounded with a misconception that "everything depends on everything else in a non-linear fashion at the same time." Not all scientific fields and institutions are *equally* malleable to economic forces in the innovation system, and not all scientists actively engage in the feedback mechanisms with innovative actors in other sectors. In short, we need a systematic structure in studying the endogeneity of science and provide a more precise analysis of when, where and why we see (or don't see) active feedbacks and interactions that make science endogenous. The second goal of this essay is to address this concern by delineating the contingencies that selectively reinforce or interfere with the endogeneity of science.

In addressing the goals of our essay, we build on Rosenberg (1982)'s statement that the "logic" of scientific progress should be coupled with a consideration of *costs* and *rewards* of scientific research that are shaped by the development of technology and its use in daily life. In short, the rate and direction of scientific research is endogenous to the innovation system to the extent that economic forces in the system, which include but are not limited to technology, shape the rewards and costs of scientific research for organizations and individuals. Thus, examining the endogeneity of science is akin to answering the following questions: How does the interplay of economic forces of the innovation system – e.g. market, technology, institutions, etc. – shape the rewards and costs of scientific research?

This essay deepens and extends this statement in several ways: First, economic and social needs in the innovation system call for the development of specific technologies, which create feedback effects on the rewards and costs of scientific research. Second, and more importantly, the feedback between science and technology is shaped by institutional features of the socioeconomic environment, such as organizational structures, norms, policies and regulations. These features can either promote or impede the feedback mechanisms that link the development of technology to scientific progress. Third, the decision to engage in the feedback loop (*i.e.* be responsive to scientific opportunities arising from economic needs in the innovation system) varies at the individual scientist level, as the costs and rewards of specific scientific endeavors are perceived differently at different stages of life cycle and levels of human capital investment.

In short, the core argument of this essay is that institutions and incentives play a central role in shaping the relationship of academic science to the innovation system. To date, the existing scholarship has shed much light upon the confluence of scientific opportunity and technological opportunity, as shown in the studies of the Pasteur's Quadrant or the paper-patent pairs (Stokes, 1997; Murray, 2002). What we like to further add to that literature is that the confluence of science and technology itself is an outcome of the socio-institutional contexts that facilitate and incentivize boundary spanning between the two.

Looking back in the history of science and technical change, we observe a variation in the endogeneity of science across different fields, different places and different times. Whereas certain innovation systems have experienced an increasingly tighter integration of science and technology over time due to institutional changes, others have not. Concurrently, certain fields of science have remained uninfluenced by socioeconomic changes in the innovative system, in contrast to other fields of science that have co-evolved with other sectors in response to such changes.

For example, the Post-World War United States is an institutional context in which the endogeneity of science has been particularly salient. What are the dynamic changes that have made science particularly more endogenous in the U.S? First, the Post-World War II rise of mission-oriented agencies has enabled the state to more directly intervene in shaping the rewards and costs of science, making academic science more endogenous to the economic needs of the nation. Second, the regulatory and institutional changes associated with academic patenting has made academia more endogenous to commercial needs of the private sector. Universities have stepped down from the ivory towers to adopt and internalize organizational structures and norms for industry boundary-spanning. Third, the revolving door between industry and academic careers, combined with increased competitive pressures within academia, has strengthened the endogeneity of academic research to industry at the individual level.

In contrast to the U.S innovation system, European innovation system is characterized by relatively weaker integration between academic science and industry technology. European universities are more strongly steeped in disciplinary focus and a culture that values knowledge for its own sake (Owen-Smith et al., 2002). In the field of biotechnology for example, the institutional separation between basic research and clinical development made European universities to be slower in the development of molecular biology, the key scientific field of industrial relevance. Combined with weaker mobility in scientific labor (Gittelman, 2000), the scientific advance of universities in Europe is not as endogenous to industry and technology as we see in the States.

The remainder of this essay is structured as follows. Our analysis starts from understanding the concept of "endogeneity of science" in the literature, by juxtaposing two contrasting views of science from the prior literature. Section 3.4 analyzes the specific reward and cost structure of the academic incentive system. In Section 3.5, we review how economic forces in the innovation ecosystem affect the rewards and costs of scientific research, thus shaping the rate and direction of scientific opportunities. In section 3.6, we discuss how scientists' endogenous responses to external opportunities are influenced by the different institutional environments and individual situations that they are embedded in. The final section concludes the essay.

3.2 Traditional Views of Exogenous Science

Modern economists have pointed to the role of ideas, knowledge and innovation as the driver of economic growth. Whereas the early neoclassical growth models assumed technological change as an exogenously provided input to the economy (Solow, 1957), the emergence of the New Growth Theory has *"endogenized"* technological change as the outcome of market incentives and intentional actions *within* the economy (Romer, 1990). In other words, the term "endogenous" is broadly used to describe certain outcomes that result from economic agents' rational and purposive decision-making in response to market forces and incentives (Rosenberg, 2000).

Researchers have often assumed that Science, as opposed to Technology, remains shielded from market forces and incentives, and thus *exogenous* to economic forces in the innovation system. This view is salient in Paul David's work, which draws on classical approaches in the sociology of science (Merton, 1973) and establishes Science and Technology as two separate domains of knowledge production with distinct incentive systems and different types of knowledge produced (Dasgupta and David, 1994).

In order to resolve the disclosure and underinvestment problem in production of inappropriable and cumulative knowledge, as identified by Nelson (1971) and Arrow (1962), the organization of Science has evolved to adopt unique incentive structures and institutional mechanisms. The Open Science regime operates by the recognition of scientific priority and a system of public (or coordinated) expenditures to reward those who contribute to cumulative knowledge production over the long term (Merton, 1973; Dasgupta and David, 1994). By rewarding researchers for their publications, Open Science resolves the contracting problem associated with producing knowledge which has strong cumulative properties and promotes its prompt and open disclosure.

In contrast, the Technology regime operates under a distinct set of rules and incentives. Research output in the Technology regime is controlled by secrecy and intellectual property, and researchers are awarded by the financial returns that result from the application and appropriation of knowledge. Thus, the scope of research in the Technology regime is constrained by the value of its potential commercial application. As a result, researchers in the Technology regime are not able to enjoy certain benefits of the Open Science regime, such as the ability to freely choose their own preferred projects, disclose their findings and choose collaborators. The wage discount that researchers undertake in order to enjoy such freedom (Stern, 2004) provides an important rationale for the prevalence of Science for a range of knowledge production activities.

It has been argued that academic institutions with public funding (*i.e.* universities, colleges and research institutes), insulated from commercial incentives and practical ends, can provide such freedom to their researchers and thus function as a wellspring of basic science research (Bush, 1945; Aghion et al., 2008). This view of *exogenous* science underlies "the linear model" of innovation, which views the process of innovation as a sequential division of labor between academic science and industry application. Although there is a debate as to whether the linear model of innovation has existed as an explicit rhetoric in the literature of science and innovation (Edgerton, 2004; Balconi et al., 2010; Godin, 2006), the concept of linearity (that scientific knowledge originating from unfettered basic research will subsequently lead to new inventions and technologies) has been widely embedded in the discourses of science policy in the twentieth-century. For instance, such belief is reflected in the public calls for increased government support for basic research (among which Bush (1945) is a representative example), the investment of early industrial labs (such as Bell Labs) in basic fundamental research, or the more recent rise of science parks (Quintas et al., 1992).

3.3 Scientific Knowledge Production as an Endogenous Process

As reviewed above, most treatments of the institutions of science have traditionally emphasized the remoteness of scientific research from practical considerations, depicting the initiation of scientific knowledge as an exogenous process. In particular, advances in basic or "pure" science in academia have been considered to create opportunities that are exogenous to competitive processes among private actors in the economy. On the other hand, drawing upon a variety of historical examples such as the early rise of thermodynamics, electrical engineering and organic chemistry, a significant body of research has discussed how scientific knowledge production co-evolves with competitive components of the innovation system such as technology, industry and market (Kline and Rosenberg, 1986; Klevorick et al., 1995; König, 1996; Murmann, 2013a). In short, an economic history of scientific research – even in academia – is often a history of the responsiveness and plasticity of scientific institutions and researchers to the objectives and requirements of multiple stakeholders in the innovation ecosystem.

Both views can co-exist as long as the endogeneity of science itself is a contingent outcome of the interplay between different researchers and different environments. Whereas scientific advances within a certain set of academic disciplines by a certain group of academics in one environment may be exogenous to factors like private R&D or technological opportunities, scientific research by a different group of academics in a different environment may be endogenous to those factors. The remainder of this essay aims to provide a structure to scattered discussions about the endogenous determinants of scientific advances in academia, and clarify the contingencies under which the endogeneity of science holds true. Put more specifically, we seek to understand the economic forces that drive scientific advances in academia and how they vary across different individuals and organizations in the innovation environment.

Following the stream of literature on technological innovation (Mowery and Rosenberg, 1991; Klevorick et al., 1995; Dosi, 1997), we highlight the interplay of *opportunities* and *incentives* for researchers (academic scientists in our context) to interact with other components of the innovation system. From the perspective of the innovation literature, advances in scientific knowledge are considered to be an important source of technological opportunities, bringing an (often assumed to be exogenous) variation to the cost and returns of technological innovation (Scherer, 1965; Jaffe, 1986). The same logic also applies to understanding the sources of scientific opportunities: as Rosenberg (1982) had argued, the "logic" of scientific progress should also be coupled with a consideration of *costs* and *rewards* of scientific research that are shaped by the development of technology and its use in daily life. Akin to what Klevorick et al. (1995) have done for the sources of technological opportunities, we identify and discuss the three major sources of scientific opportunities in Section 3.5, looking at how different components of the innovation system can shape the cost and returns of scientific research.

Incentives – the ability and willingness of researchers to exploit scientific opportunities and reap returns from their scientific research – play an important role in shaping researchers' responses to scientific opportunities. Whereas the innovation literature primarily focuses on the role of the appropriation regime at the broad industry level (such as the strength of the patent rights) (Levin et al., 1985; Cohen and Levin, 1989; Scotchmer, 2004), we address how organizational arrangements and individual preferences at a more micro level can shape an individual scientist's perception of the returns for a certain kind of research relative to others.

3.4 The Incentive System of Scientists as Economic Agents

Essentially, we view individual scientist as a boundedly rational economic agent who maximizes his utility based on given information and preferences about scientific opportunities in the innovation system. Production of scientific knowledge at the micro-level is determined by the rewards that individual scientists gain from exploiting scientific opportunities and the costs that they incur in order to exploit the opportunities. In the section to be followed, we first provide a brief review of the literature about the incentive system of scientists, *i.e.* the reward and cost structure of scientific research.

3.4.1 Rewards

Sociology and economics of science has long noted that peer recognition and prestige in academia, the "*ribbon*" (Stephan and Levin, 1992), is the most fundamental driver of scientific knowledge production under the Open Science regime (Merton, 1957; Dasgupta and David, 1994). Scientists in the Open Science regime pay tribute to the first scientist to disclose a new discovery through publication and recognize his priority with citations. By premising career rewards (such as tenure) and reputation on publications and citations, Open Science leverages the public goods nature of basic research and promotes the production of inappropriable knowledge. The practice of prompt disclosure and systematic citation enables scientific knowledge to be shared among scientists and serve as the "shoulders of giants" for subsequent research.

Although publications and citations are the most important tokens of individual status in academia, other forms of prestige include prizes, awards and affiliation with prestigious institutions or honorific societies: Nobel Prize, Fields Medal, the National Academy of Sciences membership, HHMI appointment, etc (Higgins et al., 2011; Azoulay et al., 2013; Cole and Cole, 1967). Whereas the reward structure just based upon the sheer quantity of publications and citations may lead to prolific yet trivial research, alternative forms of recognition that prioritize quality reinforce the production of creative and impactful research (Cole and Cole, 1967).

Another extrinsic motivation for scientific research is the financial incentive in the form of wages and entrepreneurial gains. Although it has been argued that scientists in general are known to sacrifice monetary gains in order to be a part of the Open Sciece regime (Merton, 1957; Dasgupta and David, 1994; Stern, 2004), recent works show that academics have heterogenous preferences and many of them are sensitive to wages and publication-based financial incentives (Roach and Sauermann, 2010; Stuart and Liu, 2010).

With the rise and growth of entrepreneurial science during the past few decades, financial gains through patenting and licensing have become an important incentive for scientific research (Lach and Schankerman, 2008). In the "Private" regime, researchers are incentivized by the ability to appropriate the value of knowledge through legal exclusion (patenting) and commercialization, rather than their ultimate impact on follow-on research (Levin et al., 1987; Kremer, 1998; Scotchmer, 2004).

3.4.2 Costs

The pursuit of economic rewards through scientific research incurs significant costs. To begin with, scientists first have to incur *the cost of learning* to be able to produce scientific knowledge. Scientific research at the individual level is a cumulative and path-dependent process in that the stock of one's prior knowledge in a scientific area (*i.e.* human capital investment) determines the productivity of one's research in the area. Pursuing a new research opportunity may require an individual to enter into a new field in which he has little prior knowledge, and the cost of learning becomes an effective barrier to entry into new areas. Over time, the human capital investments (*i.e.* education) required to operate at the frontier of science increases over time, building a higher entry barrier between scientific areas and thus promoting specialization of scientific research (Jones, 2009).

Second, *the cost of research* acts as a major constraint to pursuit of research opportunities. Modern scientific research requires access to costly equipment, materials and manpower[1]. The cost of maintaining a research laboratory is known to have dramatically increased in many scientific disciplines, from applied sciences like biomedical sciences and engineering even to basic research like physics and astronomy (Stephan, 2012).

For example, large particle accelerators and colliders are indispensable equipment in order to pursue research opportunities and conduct experiments in particle physics. The costs of building such large accelerators are so great that only a handful of institutions (such as CERN, Brookhaven National Laboratory and Fermilab) was able to build them. The capacity and availability of this equipment thus have become a constraining bottleneck for the pursuit of experimental particle physics. In biomedical sciences, research materials like cell lines and oncomouse, in addition to equipment, are an important part of the cost structure.

Given that modern scientific research is mostly carried out by teams rather than single individuals (Wuchty et al., 2007; Jones et al., 2008), the cost of collaboration and communication is an important part of research cost. The cost may include opportunity cost of time taken to travel and interact with collaborators (Catalini, 2012), as well as communication costs between geographically distant institutions and individuals (Agrawal and Goldfarb, 2008). Empirical studies have found that such costs not only shape the process of selecting collaborators, but also the fundamental quality and novelty of scientific projects.

Third, for scientists who are incentivized by the potential entrepreneurial gains of research opportunities, the *cost of appropriation* (of research outcomes) influences their decision to pursue the research. The cost of appropriation may be twofold: the transaction cost of appropriation and the opportunity cost of appropriation. First, the perception of time and resource costs of interacting and negotiating with licensing officials, technology transfer offices and licensees (firms) can deter academic scientists from engaging in patenting (Owen-Smith and Powell, 2001). Scientist will be more incentivized to pursue research projects with a licensing potential to the extent that monetary gains outweigh the transaction cost for patenting and licensing of research

[1]Please refer to Chapter 5 of Stephan (2012) for detailed discussion of this topic.

outcome. Second, the appropriation of research (through commercialization) will come at the opportunity cost of sacrificing academic freedom to choose one's own research agenda and publish research outcomes (Stern, 2004; Tartari and Breschi, 2012). Tartari et al. (2012) call this "Mertonian barriers", as opposed to "Williamson barriers" of dealing with the rules and regulations of the university and conflicts over IP with industry partners.

3.5 The Endogeneity of Scientific Opportunities to the Innovation Ecosystem

We argue that science advances in a constant state of disequilibrium, in which external shocks to the rewards and costs of scientific knowledge production continuously update the opportunity set of individual scientists. Scientific opportunities, which we define as the possibilities for new understanding about the world (*i.e.* scientific knowledge) that may (or may not) be utilized for potential economic benefits, arise as a result of endogenous responses to the external environment. Scientists respond to the rise of opportunities by deciding which area of scientific research they would engage in and how much effort they would exert.

We argue that scientific opportunities are shaped by three distinct yet interrelated economic forces in the innovation system: (1) Economic and social criteria of stakeholders and (2) Technological innovation and industry demands, and (3) Government policies and regulatory changes.

3.5.1 Economic and Social Criteria of Stakeholders

The ability of society to generate scientific knowledge that contribute to generation of new technology is shaped by the research agenda and interests of the society (Mokyr, 2002). At this current juncture, the vast majority of scientific research is funded by mission-oriented agencies, industry associations, or directly by the private sector. By and large, sustained support for cumulative scientific research is focused on areas where funders perceive pragmatic benefits from that investment. The benefits from funding what may seem to be "pure" scientific research come from the potential to have these researchers work in an area of pure scientific study that is nonetheless highly complementary with the funder's pragmatic objectives. Indeed, it is fair to say that the most significant growth in the sciences over the past century have been centered on areas where the linkage between pure scientific research and key applications are strongest.

Looking back the history of wars and economic crises, we are able to clearly see how economic needs of the state have shifted the direction of scientific research. In case when there is a sudden exogenous shock to the rate of return for certain innovations, the state government and the industry respond to the shock by supporting national labs and universities to conduct scientific research in relevant areas. Such initiatives foster the entry of scientists into the relevant areas by both increasing the rewards to research (by providing challenging "puzzles" and the "ribbons" for solving them) and decreasing the cost of research for the researchers (by enabling easier access to funding and equipment).

For example, during the World War II, the demand for natural rubber skyrocketed due to a sharp spike in military consumption: the construction of military airplanes, tanks and battleship required tons of rubber, not to mention the rubber needed for military footwear, clothing, and equipment. However, the war cut off U.S access to natural rubber supply, and the nation was in desperate need for synthetic rubber.

In response to this economic shock, President Roosevelt appointed the Rubber Survey Committee in August 1942, which included scientists James B. Conant, president of Harvard University, and Karl T. Compton, president of Massachusetts Institute of Technology (American Chemical Society National Historic Chemical Landmarks, 2015). In collaboration with the leading U.S. rubber manufacturing companies such as Firestone and Goodyear, university laboratories performed fundamental research on the chemical structure of rubber and the mechanism of synthetic rubber polymerization.

Similarly, the energy crises in the 1970s caused by the OAPEC's oil embargo in response to the U.S involvement in the Arab-Israeli War, increased the rate of return to alternative energy such as wind and solar power. Hence the U.S. government, through the DOE investment, induced academic institutions to actively engage in aerodynamics research, which is a crucial knowledge input for high-quality wind turbines (Mazzucato, 2013).

In the U.S., academic research for such pragmatic benefits is mostly driven by the support of mission-oriented funding agencies, such as NSF, NIH, DOD, DOE and DARPA. The economic and social criteria of the society is reflected in the construction of these agencies, as well as the fluctuations of funding that is funneled into each agency. The private and public sector demand for healthcare and defense has pushed the government to give NIH, NASA and DOD a lion's share of federal R&D budget over other agencies, so that research efforts can be concentrated in areas of science that are of relevance to these industries in particular.

This inevitably means that scientific research in areas at the lower end of the (economic) priority ranking is given less funding, regardless of its scientific potential. Whereas $69.5 billion will be given to defense R&D (both DOD and DOE defense programs) in 2015, the 2015 budget has proposed merely $560 million for the Environmental Protection Agency. This raises the issue of whether there are important areas of scientific inquiry that, despite the potential for scientific advance, receive little funding and therefore experience little progress. It is arguable that climate science has traditionally been this sort of area, at least until recently. It was only when the impact of climate science on overall industrial development was recognized that significant resources began to be devoted to its exploration. Climate science was only able to take off after the enactment of the Global Change Research Act and the launch of the U.S. Global Change Research Program.

The strong influence of mission-oriented agencies raises the possible concern that scientific research output may be sacrificed to the extent to which these funding agencies prioritize production of application-specific knowledge in lieu of fundamental knowledge. For example, Goldfarb (2008) argues that NASA's goal-oriented focus on aerospace engineering has had a suppressing effect on academic productivity in fields of academic importance but weak linkage to practically useful result. Such effect may be aggravated by the fact that the mission-oriented agencies' operation is supported by Congressional funding, which is shaped by the short-term horizon of the Congress that wants to see tangible research output during its term (Cohen and Noll, 1986).

3.5.2 Technological Innovation and Industry Demands

While the linear model emphasizes the influence of scientific discovery on technological innovation, a range of historical and empirical studies points to the central role of technology itself in shaping the process of scientific discovery and the productivity of scientific research. Technological change is an important impetus for the identification of novel phenomena, the statement of novel hypotheses, and the development of novel methods for measurement and testing. While the "feedback" from technology to science has been little more than an afterthought in most formal theoretical treatment of the relationship between science and technology, a wide body of evidence highlights the central importance of technological change in shaping the nature of scientific advance. Technological progress itself (and the ability of scientific researchers to exploit new technology) is a fundamental requirement for scientific advance over the long term.

Industrial Innovation and New Product Inventions

The emergence of new disciplines such as chemical engineering in the twentieth century reflects how basic research has co-evolved with industry technology. Prior to the introduction of Arthur D. Little's "unit processes" in 1916, industrial applications of chemistry were conducted by trial-and-error with little learning across applications. The conceptual breakthroughs in chemical engineering during the 1920s led to a rapid reorientation of the relationship between basic science and technological innovation. In particular, chemical engineering researchers at institutions such as MIT were able to develop solutions that applied across a wide range of industrial applications, and, in doing so, were able to identify new questions and phenomena that spurred further research itself. Simply put, the engineering discipline of chemical engineering was itself a "general purpose technology" from the perspective of industrial innovation (Rosenberg, 1998). Murmann (2013b) reinforces this role of co-evolution by carefully documenting the step-by-step process by which the scientific domain of chemistry and the industrial domain of chemicals influenced and reinforced each other over the second half of the 19th century.

Looking at the evolution of scientific disciplines that stand at the intersection of basic and applied research, the development of some specific new product, that is perceived to have great commercial potential, often has provided a powerful stimulus and feedback to scientific research. A major technological breakthrough provides a strong signal that further improvements in new technology would open up a new set of profitable opportunities, which generate strong positive feedbacks in the scientific community. The problems and anomalous observations encountered in the process of industrial R&D serve as powerful stimuli to the direction of scientific research in the academic community as well as the industrial research laboratory.

This was dramatically demonstrated in the case of the advent of the transistor, which was announced at Bell Labs in the summer of 1948[2]. Before the advent of the transistor, solid-state physics had previously attracted the attention of only a small number of researchers and was not even taught at the vast majority of American universities (MIT, Princeton, Caltech). However, the development of the transistor dramatically upgraded the potential financial payoff to solid state physics research. Within a decade of the invention, solid state physics rapidly transformed into one of the largest subdiscipline of physics. Both the university community and private industry entered into solid state physics research, and the number of basic publications in semiconductor physics rose from less than 25 per annum before 1948 to over 600 per annum by the mid-1950s (Herring, 1957).

A similar sequence can be seen in a wide variety of industries. More recently, the development of laser technology suggested the feasibility of using optical fibers for communications technologies and data processing. The potential financial payoffs

[2]For a more comprehensive review of this historical event, refer to Rosenberg (2007).

to optical fiber innovation naturally led to a great resurgence of optics as a field of research in the 1960s and after. The invention of electric car dramatically increased the potential payoffs for high-power battery research, as rechargeable batteries function as the most important and expensive component of the vehicle. The fact that the demand and needs of the electric car is pushing the frontier of material sciences (in battery-related areas) implies that complementarity between technological innovations plays an important role in shaping the direction of scientific research.

Research Technology and ICT

Whereas the above discussion was focused on the role of technology in shaping the economic returns (*i.e.* rewards) to scientific research, technology can shape scientific opportunities by decreasing the burden of research cost needed for scientific analysis, instrumentation and communication.

Most importantly, the rapid advance of modern science owes to the invention of computer as a general purpose technology and the dramatic increase in computing power. The availability of greater computing power not only influences research productivity (the rate), but also the way that research is conducted (the direction). Although the advance in computing power has influenced almost all scientific disciplines, we will focus on the history of computational chemistry for an illustrative purpose.

Computational quantum chemistry was first introduced by the work of Walter Heitler and Fritz London as early as 1927. However, it was only until the development of computer technology that computational chemistry became an object of systematic scientific research. Having gained access to computing power, they were able to pursue novel theoretical questions about the properties of molecules or reaction mechanisms, which would not have been possible with human calculation. We observe similar trajectories in the history of computational physics and computational biology.

Technological advances in instrumentation and measurement allow scientists to discover and pursue novel research opportunities. The specific nature and environment for technological change does not simply change the range of tools and instruments that scientists have to work with but changes the very questions that Science asks and explores. Consider the environment of Albert Einstein prior to the development of special relativity in 1906 (Galison, 2000). At the time, Einstein was working as a patent officer in Bern, a city whose increasingly cosmopolitan landscape was dominated by electromechanical clocks. The technology of clocks was being increasingly refined to offer synchronized timing across distance (primarily for the purposes of automated train switching and the like). It is in this particular environment – where Einstein was at the center of the rapid development of automated clocks and automated timing systems – that Einstein developed his fundamental conceptual breakthrough that modern physics must relax the Newtonian concept of absolute time.

Finally, the advancement in information and communications technology also shapes the scope of scientific opportunities by enabling collaboration among distant organizations (Agrawal and Goldfarb, 2008). The advent of Internet, by enabling information to be analyzed and accessed at minimal cost, has exposed scientists to a wider range of research opportunities that would otherwise have been inaccessible. For example, The Human Genome Project shared the sequence of the human genome and analytical tools on the Internet, providing democratic access to research opportunities for genetic researchers all over the world (Powell and Snellman, 2004).

3.5.3 Government Policies and Regulatory Changes

Finally, government policies for and regulatory shocks to approval, funding and appropriation of scientific research can either restrain or unleash potential scientific opportunities in the innovation system. We provide two examples of the important regulatory events that caused a radical shift to the incentive structure and the opportunity set of academic researchers in the U.S. – the Diamond v. Chakrabarty ruling and the Bayh-Dole Act.

In 1971, Ananda Mohan Chakrabarty, a genetic engineer at General Electric, succeeded in genetically engineering for the first time a new species of *Pseudomonas* bacteria which breaks down crude oil and thus can be used to treat oil spills. General

Electric developed and filed a patent application for the bacterium listing Chakrabarty as the inventor, which was the first U.S. patent application for a genetically modified organisms. The patent application was initially denied by the Patent Office because living organisms were not thought to be a subject matter of patent protection. When the United States Court of Customs and Patent Appeals ruled in favor of Chakravarty's patent, Sidney A. Diamond, Commissioner of Patents and Trademarks, appealed to the Supreme Court, leading to the famous "Diamond v. Chakrabarty" case. On June 16, 1980, the Supreme Court ruled that "a live, human-made microorganism is a patentable subject matter".

Patentability of genetically modified organisms was an important determinant of the potential economic profits that can be derived from scientific research under this technology. The huge market potential of medicinal and agricultural technology, now enabled to be tapped into with the regulatory approval from the government, has driven the entry of academic and industrial scientists into disciplines like biochemistry, genetics, microbiology and molecular biology.

The entry of academic scientists into disciplines with potential financial payoffs has been promoted by another regulatory event: the enactment of the Bayh-Dole Act in 1980. Before the enactment of the Bayh-Dole Act, the ownership of patents that were funded by federal money was granted to the federal government. By allowing universities to pursue ownership of patents that were federally funded, the Bayh-Dole provided monetary incentives to academic researchers. The enactment was followed by the sharp rise of patenting and licensing activities of universities, especially in areas characterized by strong economic significance of intellectual property like biomedical (Mowery and Sampat, 2005; Mowery et al., 2001). Recent empirical studies find that the rise of patenting and commercialization allowed by the Bayh-Dole Act has had a positive impact on the rate of both basic and applied research (Thursby and Thursby, 2011). As for the direction research, scientists seem to be moving to areas of commercial interest to exploit the opportunities to capitalize on their research outcome (Azoulay et al., 2009).

Government policies and bylaws can prohibit or regulate research opportunities in certain scientific areas. For example, genetic engineering of the human genome is an scientific area that has been strictly prohibited by the government due to ethical concerns. Stem cell research, especially those involving human embryonic stem cells, has been regulated by the government, although the extent of regulatory restrictions varies across countries or their ruling parties. Changes in government policy and regulations has led to ebbs and flows in scientific opportunities related to this area of research.

In the U.S., the Dickey Amendment passed by the Congress in 1995 prohibits the use of taxpayer dollars in the creation or destruction of human embryos "for research purposes." In 2001, President Bush approved federal funding to a limited number of embryonic stem cell lines but the funding was rescinded. President Obama overturned the policy in 2009 by expanding the number of stem cell lines available to researchers, unleashing a set of scientific opportunities for scientists in this area of research. In January 2013, the Supreme Court dismissed the lawsuits against NIH by scientists who opposed to the use of human embryonic cells in NIH-funded research, confirming the government support for embryonic stem cell research going forward.

3.6 The Role of Institutions and Individuals in Mediating the Endogeneity

3.6.1 Institutions

While economic models of ideas-driven growth (such as Romer (1990)) model the inter-temporal spillovers associated with knowledge production as an exogenous parameter, historical and empirical studies suggest that the relationship between science and technological progress is endogenous to the institutional environment. In the absence of an effective institutional environment, the ultimate impact of scientific research on technological innovation, and vice versa, may be quite limited. Subtle institutional arrangements (such as the governance of the "university-industry interface") shape the incentive and ability of scientists to discover and pursue scientific opportunities of economic value. At the same time, the institutional arrangements also play a crucial role in realizing and capturing the economic and social benefits of scientific research. In short, rather than the linear model, the relationship between scientific discovery and technological innovation is more usefully conceptualized as a bilateral and co-evolutionary system mediated by institutions. In the paragraphs to be followed, we examine the specific ways in which the institutional environment can facilitate scientists' pursuit of research opportunities in the innovation system.

Institutions for Industry Boundary Spanning

The feedback effect between academic science and industry technology is mediated by the institutional capacity of academic organizations to promote university-industry boundary spanning. Industry boundary spanning through means of patenting, consulting and research agreements (among many others) can shape the direction of research by bringing academics to new research opportunities of industrial relevance. The opportunities provide not only the economic incentives of commercialization (Lach and Schankerman, 2008; Thursby et al., 2007), but also the exposure to a broader set of novel research questions and methods (Evans, 2010).

Although the norm of "entrepreneurial university" (Etzkowitz, 1998) and the practice of technology transfer have become widespread in academia, universities differ in their institutional capacity to promote and enable industry boundary spanning. The organizational resources, capability and experience of university technology transfer offices vary considerably, affecting the transactional cost of engaging in technology transfer and start-up activities (Lockett and Wright, 2005; Powers and McDougall, 2005; Siegel et al., 2003). Other types of boundary-spanning infrastructure such science parks and incubators (Link and Scott, 2003; Phan et al., 2005; Rothaermel and Thursby, 2005) allow university scientists to easily access new research opportunities of industrial relevance.

By facilitating the functioning of economic incentives, stronger organizational capability for industry boundary spanning will better incentivize university researchers to engage in areas of science that are likely to provide monetary outcomes. The university's organizational capability for boundary spanning simultaneously incentivizes industry partners to seek university researchers for collaboration and technology transfer, thus widening the horizon of research opportunities for academics.

Institutions for Local Economic Development

The endogeneity of university research to opportunities in the industrial environment is mediated by the institutional mandate of the university to be responsive to the needs and concerns of the local economy. Particularly in the United States, the university system has historically been quite responsive to local economic concerns and research has been closely integrated with local technological development (Rosenberg and Nelson, 1994; Mowery and Rosenberg, 1999).

The distinctive features of the American university system is most notably reflected in the establishment of a system of state-level land grant universities in the Merrill Act of 1862. The mission of the land grant university was predicated upon deriving research goals from societal needs at the time: namely, the pursuit and dissemination of agricultural and engineering knowledge for the local economy. By adopting the practice of the county agent, land grant universities not only delivered new information and knowledge to individual farmers, but also identified problems and concerns of local farmers at the county level for agricultural specialists to work on (Rosenberg and Nelson, 1994).

The local industrial needs that initiated the foundation of land grant universities were not confined to agriculture only. Massachusetts Institute of Technology, although it did not have an agricultural experiment station like many other land grant state universities did, was founded on a mission "*to promote the liberal and practical education of the industrial classes*", aiding "*the advancement, development and practical application of science in connection with arts, agriculture, manufactures, and commerce*" (Stratton and Mannix, 2005; O'Shea et al., 2007). MIT's prioritization of local industry needs led them to quickly adopt and introduce new engineering disciplines ahead of other schools. In response to the invention of the dynamo in 1882 and the rising economic importance of electricity, MIT started offering its first course in electrical engineering in the very same year. Similarly, in response to the rising interest in aerodynamics among naval constructors at the Boston Navy Yard, MIT began a program in aeronautical engineering (Rosenberg and Nelson, 1994)

Institutions for Disciplinary Boundary Spanning

The impact of new scientific opportunities upon the rate and direction of academic research is mediated by the extent to which research questions from one discipline can spill over to other disciplines and lead to novel recombination of knowledge. The importance of institutions in shaping interdisciplinary spillovers seems to be increasing over time, particularly in the life sciences. Perhaps no single institutional innovation captures this than the rise of the Academic Medical Center (AMC) over the last half century (Rosenberg, 2009).

While the relationship between university life sciences research and medical innovation was historically modest (indeed, it is likely that chemistry played a far more important role as a source of industrial application than biology in the first half of the twentieth century), the explosion in life sciences research after the establishment and rapid growth of the National Institutes of Health offered an opportunity to radically alter the orientation and industrial integration of life sciences research.

Leading university researchers and administrators embarked on a series of "institutional experiments" that resulted in the development of large, multidisciplinary research centers, often linking medical school teaching, patient care, and basic university life sciences department such as biology, chemistry, and engineering. This institutional change has allowed active boundary spanning between basic and applied research, allowing questions of applied nature to inspire basic research and vice versa.

For example, at Stanford University, Fred Terman embarked on an ambitious program of attracting grants and leading faculty to establish a set of new basic research departments that would be housed within the Stanford Medical School, including Biochemistry and Genetics. Notably, Terman undertook an effort to recruit young but leading researchers such as Alan Kornberg, Paul Berg, and Joshu Lederberg, all of whom would ultimately to win Nobel Prizes for the fundamental discoveries.

However, by giving these researchers opportunities to build new departments within a medical school (as opposed to a traditional arts and sciences college), Kornberg, Berg, and Lederberg were able to focus on research questions and attract faculty who would engage with applications of their discoveries in an appropriate institutional context.

From their inception, the Stanford Medical School's 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. Indeed, though his origins were in extremely basic research, Arthur Kornberg ultimately became quite directly involved in technology entrepreneurship himself, serving as a founder or on the scientific advisory board of companies such as ALZA and DNAX.

Most importantly, the ability of Kornberg and others to bridge the university-industry divide seems to be closely tied to the distinctive institutional arrangements governing AMCs such as Stanford; as a consequence, the spillovers arising from life sciences research is thus endogenous to the institutional environment in which that basic research is conducted. In other words, the rise of the Stanford AMC – and others like it at UCSF and the Harvard Medical School – is grounded in successful institutional experimentation that allowed medical school research to simultaneously exploit the wide range of scientific and engineering disciplines located within a university while also linking that research directly to the ability for significant levels of technological innovation (Rosenberg, 2009).

3.6.2 Individuals

Individual researchers' endogenous responses to the technological and economic environment are not only mediated by the features of the academic institutions that they are embedded in, but also by their individual preferences and career concerns. Individual preferences and career histories shape the researcher's perception and evaluation of rewards and costs involved in pursuing certain types of scientific opportunities (in lieu of others). Due to heterogeneous opportunity cost of pursuing research opportunities, researchers thus make heterogeneous choices in response to the same set of opportunities in the innovation system.

Individual Preferences

Recent studies of scientists have argued that academics are heterogeneous in their preferences for open science and basic research (Stern, 2004; Sauermann and Roach, 2014; Agarwal and Ohyama, 2013). Such differences may shape the extent to which researchers will respond to research opportunities of industrial relevance and applied nature. Individuals with entrepreneurial orientations may choose to select themselves into particular institutional environments which provide better access to entrepreneurial opportunities. On the other hand, researchers with strong preference for fundamental and basic research will intentionally choose an institutional environment that can shield him from applied concerns, or a research trajectory that is detached from practical concerns.

Individual preferences are not just innately determined, but also socially constructed: a researcher's social networks shape his perception of opportunities in the research environment. Prior research has found that academics' entry into industry engagement and entrepreneurial activities is shaped by local peers (Stuart and Ding, 2006; Bercovitz and Feldman, 2008; Tartari et al., 2014).

Finally, an individual researcher's evaluation of research opportunities is shaped by his access to resources, which is often determined by his academic capability. Goldfarb (2008) argues that mid-level academic researchers (in terms of academic capability), constrained by the lack of outside funding options, have a stronger incentive to cater to research needs of mission-oriented sponsors (such as NASA) – and thus endogenous to industry and government needs. On the other hand, the research trajectory of top-tier researchers may be determined exogenously to such needs, given than they are sufficiently funded by university budget or grants with no strings attached.

Human Capital Investment and Life Cycle

Even holding individual preferences constant, the rewards and costs of pursuing certain research opportunities may still vary according to the scientists' prior human capital investment as well as his stage in the academic life cycle. In other words, a scientist's ability and incentive to seize new research opportunities and strike out a novel research trajectory is shaped by his prior research trajectory.

Being on top of the knowledge frontier requires scientists to make significant human capital investments in specific fields and disciplines (Jones, 2009). With the reputation-based reward system and the Matthew effect in academia, there exist strong incentives for academics to invest in research during the early stage of career (Levin and Stephan, 1991; Carayol, 2007). This human capital model suggests that scientists become vested in their existing research trajectory as they age and become resistant to new theories and opportunities (Diamond, 1986; Levin et al., 1995).

The scope of prior human capital investment also seems to be a significant factor that shapes scientists' responses to new research opportunities. For instance, a researcher with a broader scope of research will have a higher chance of incorporating new opportunities into his existing research trajectory, just as interdisciplinary institutions produce more novel combinations of ideas. This argument is supported by Teodoridis (2014), who finds that generalists exhibit a stronger response to opportunities for knowledge creation enabled by the reduction in the cost of motion-sensing technology.

3.7 Is Science Always Endogenous?

Looking back at the history of science and technical change, we observe a variation in the endogeneity of science to industry and innovation across different places and times. The direction of scientific advance is endogenous to the amount of opportunities in the innovative system for scientists to exploit, as well as stronger incentives for them to be responsive to those opportunities. Juxtaposing the U.S. and the European innovation system for example, we can see how differences in institutions and incentives resulted in a tighter integration of science and technology in the former – *thus making science more endogenous*– compared to the latter.

First, in the Post-World War II United States, the linkage between science and economic needs of the nation have become tighter with the rise of mission-oriented agencies. Governments and states, which are major funders of academic research, are pursuing more concrete economic initiatives for the development of specific technologies and industries. This is not to deny that the economic needs of the state have always influenced the advance of science – since as early as when the ancient Egyptian dynasty promoted math and astronomy for the prevention of floods and the construction of Pyramids in the Nile Valley. Rather, the change has been in the way that national R&D is structured and institutionalized.

Over the past century, mission-oriented agencies (in agriculture, defense, health, etc.) have grown to dominate science funding in not only U.S. but also most OECD nations (Mowery, 2010). In the U.S. for example, the research budget of NSF, which focuses on the promotion of fundamental science rather than a specific mission, is less than a quarter of NIH (Sampat, 2012).

In the past when the military had primarily been in charge of driving technological R&D, the linkage between science and technology was not as tight. It was the Post-World War II establishment of individual mission-driven funding agencies, such as the establishment of National Aeronautics and Space Agency and Advanced Research Projects Agency in 1958, and The Department of Energy in 1977, that has brought specific agency goals and academic research closer to each other.

By enacting federal laws to promote R&D programs and allowing the Congress to determine budget allocation for funding agencies (which would then be distributed to academic institutions), the government has become institutionalized to directly intervene in the reward and cost structure of scientific research. Policy initiatives prioritize specific areas of interest and promote mission agencies to funnel funding into relevant areas of science. Examples include the National Cancer Act of 1971 signed by then President Nixon, the 21st Century Nanotechnology Research and Development Act signed by President Bush in 2003 and many more.

The second change in the U.S innovative system has been in the linkage between academic science and industry innovation. This institutional change has been driven by the Bayh-Dole Act, which allowed universities to obtain patents on federally funded research. The Federal Technology Transfer Act of 1986 also provided the legal structures that allowed collaborative research agreements between public nonprofit organizations (such as the federal laboratories) and private sector corporations (Slaughter and Rhoades, 1996).

Prior to such institutional changes, the linkage between federally funded academic research and the private industry sector because the incentives did not exist for academics to engage in commercialization. With the regulatory change that brought academia and industry closer together, the agenda of government agencies has expanded to include "commercial competitiveness" and started to support science and technology geared to help industry (Slaughter and Rhoades, 1996). In response, academia has evolved to adopt and internalize organizational structures and norms for industry boundary-spanning, such as technology transfer offices, start-up incubators and tenure policies that also reward industry contribution.

Third, in addition to formal and informal collaborations *across* individuals based in industry and academia, the revolving door between industry and academic career *within* individuals has also strengthened the endogeneity of academic research to industry at the individual level. Whereas in the past it had been thought that traditional Ph.D training should exclusively serve the purpose of training academics, the broader employability of doctoral degree holders have increasingly expanded beyond the academic labor market (Enders and De Weert, 2004). The pyramid structure of academia, combined with the oversupply of doctoral students, is making it more difficult for researchers to secure a permanent PI position within academia (Stephan, 2012). One way for academics to diversify their job search risks is to pursue industry-relevant fields of science. Many R&D-intensive companies, especially in industry sectors like chemicals and biotechnology, are offering training programs for postdoctorates, many of whom eventually return to universities to pursue academic careers. As intersectoral job changes become more commonplace, the direction of academic research becomes more endogenous to the external sector.

In contrast to the U.S innovation system, the European innovation system is characterized by the relatively weaker integration between academic science and industry technology. In contrast to the U.S. system in which academic research has been primarily governed and funded by mission-oriented agencies, academic research in Europe has been governed by the research council system, which has been been traditionally run by scientists for the benefit of science (Leydesdorff et al., 1998). Compared to the U.S., European universities are more strongly steeped in disciplinary focus and a culture that values knowledge for its own sake. This is also reflected in the fact that highly prestigious research institutes in the Europe are hierarchically organized around a single discipline, whereas research organizations in the U.S. bring together multidisciplinary researchers to address common research goals (Owen-Smith et al., 2002).

Despite the heavy investment in university research as well as policies to transfer the research output to the commercial sector, the lack of proper university-level incentives has interfered with the integration of academia and industry in Europe (Goldfarb et al., 2001). In the case of biotechnology for example, the institutional separation between basic research and clinical development made European universities slower in the development of molecular biology, the key scientific field of industrial relevance. Combined with weaker mobility in scientific labor (Gittelman, 2000), the scientific advance of universities in Europe has not been become as endogenous to industry and technology as we see in the States.

3.8 Conclusion

For the last few decades following the advent of the endogenous growth theory, we have seen an increasing emphasis on knowledge spillovers as the engine of economic growth. In particular, scientific knowledge produced in academia is considered to be the integral source of innovation and entrepreneurship. Given the weight given to the topic of academic spillovers in both scholarly and policy discourses, an important question becomes what shapes the rate and direction of science in academia.

This essay provides an overview of the endogenous economic forces that shape the rate and direction of scientific advances in academia. Drawing on a rapidly growing body of research on economics of science, we synthesize the literature on the endogeneity of science in a following statement:

- Production of scientific knowledge is not only shaped by the internal incentive system within academia, but also by the extent of scientific opportunities created by external economic forces in the innovation system such as 1) the economic and social criteria of stakeholders (*e.g.* funders, users, etc.), 2) technological advances and industrial demand, and 3) government policies and regulatory changes.

- Organizations and individuals differ in their incentives to respond to the opportunities in the innovation system, depending upon 1) institutional features for boundary-spanning and 2) individual preferences and life cycle.

- There exists a variation in the endogeneity of science to industry and innovation across different places and times. Recent institutional changes such as the establishment of mission-oriented agencies, regulatory support for industry boundary-spanning, have made science more endogenous to the broader innovation system in certain contexts compared to others.

To summarize, our analysis identifies and integrates two broad strands of literature on the endogeneity of science: opportunities at the macro level and incentives at the micro level. An important direction of empirical research is to identify and measure the impact of macro-level shocks on scientific productivity. For example, beyond measuring how a demand shock can shape technological innovation as realized in R&D expenditures and patents, what would be its upstream effect upon relevant scientific output in academia? The next question would be to further investigate the agents of such endogenous change and how different types of individuals will selectively respond to different incentives to shift their direction of scientific research.

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