Sources of Biological Innovation for Agriculture: the Roles of Public and Private Research Institutions in Generating Technological Trajectories

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ABSTRACT:

This paper introduces a comprehensive data set of patents issued in the U.S. between 1975 and 1998 in the biological sciences applied to plant agriculture. Novel sampling techniques are employed along with a multinomial econometric model to analyze the differences in patenting across the R&D sectors of the economy.

Hypotheses are presented that universities and public institutions specialize in basic research and patent research results with the greatest uncertainty in terms of the value of the outcomes; entrepreneurial private innovators such as startup companies and individual inventors specialize in turning basic innovations into applied innovations and marketing these for industrial use, and undertake research of somewhat more certain value; corporations specialize in incremental applied innovations that concentrate on the production of final outputs, not on enabling further innovation, and patent with greatest certainty of the value of outcomes.

Analysis of the distributions of adjusted forward patent citations, an established proxy for patent value, reveals significant differences between university, startup, and corporate inventors in terms of the mean values and the level of uncertainty of values their respective patented inventions, with universities and public research organizations achieving the highest mean value and highest variance of values, startups with an intermediate mean and variance of value, and corporations with the smallest mean variance of value. Discrete outcome estimation results are preliminary, but appear to support the hypothesis of universities undertaking early research in the evolution of technologies, followed by startups, with corporations concentrating in later developments.

1. INTRODUCTION

It has been contended in some corners that the generation of biotechnologies for agricultural application has become the domain of large multinational corporations and that they have eclipsed the role of the public sector in providing agricultural technologies. However, it may be countered that, while the managers of major agricultural enterprises may spend their days competing against one another with new releases of the latest technologies designed to win greater market shares, those same managers are kept up at night with real worries about what next unexpected development will come out of a university laboratory.

In that spirit, this paper seeks to demonstrate that each of the three basic R&D sectors of the agricultural economy enjoys particular comparative advantages in different parts of the innovation process, and that the three sectors work together in a dynamic process to carry new technologies from initial ideas to implemented products. The three sectors include (1) universities and public research institutions, (2) small entrepreneurial private innovators such as startup biotech firms, small independent seed companies, cooperatives and growers associations, and individual inventors, and (3) established (incumbent) corporations, including agrochemical producers, pharmaceutical and food corporations, and the largest established seed companies.

Three basic hypotheses about the economic roles of the three R&D sectors are posed as follows:

1. Universities and public institutions specialize in basic research and undertake projects of more uncertain value.

2. Small private innovators such as biotech startups, small independent seed companies, or individual inventors specialize in turning basic innovations into applied innovations and the marketing of these for industrial use; they undertake projects that are less uncertain than the work undertaken in universities in terms of value. They are vehicle for the development of technology portfolios characterized by greater uncertainty of commercial value than those typically pursued by incumbent corporations, but which are often internalized by incumbent corporations.

3. Incumbent corporations specialize in incremental applied innovations that concentrate on the production of final outputs, not on enabling further innovation, and are characterized by less uncertainty than either universities or startups in the value of what they patent.

The general subject of the differential and complementary roles is debatable in principle and is challenged in specific ways. With the widespread emergence of molecular biology and genetics as agricultural technologies, the establishment of new intellectual property protection of life forms in many countries, and the rapid growth and consolidation of the agricultural inputs industry around these new proprietary biotechnologies, longstanding models of the relationship between the research efforts of the public sector and private industry in the field of agriculture are being flexed, changed, and challenged.

Based on the general agreement that technology is a key determinant in economic growth at the national level (Solow, 1957; Romer, 1990) technology generation by public institutions and captured for private use should be, in theory, beneficial to everyone, yet critics argue that universities and pubic researchers have gone too far in "behaving more like for-profit companies" and are neglecting their funded mandate to provide public services and commercially unbiased research (Press and Washburn, 2000). To what extent do universities look like for-profit companies, in terms of the 'for-profit' output that their R&D generates?

Others note with concern the discrepancy between intensive private investments in the research and development of proprietary industrial agricultural technologies in industrial countries, where agricultural productivity is already high and food supply is in surplus, and the diminutive public provision of technologies designed for and deployed in problematic areas of the globe where needs for agricultural and nutritional solutions are most acute (and therefore the potential for social welfare gains are highest), such as environmentally sustainable agricultural systems in sensitive ecosystems (Altieri, 1997) and productivity improvements for impoverished regions in developing countries (de Janvry et al, 1999). The actual roles of the different sectors, particularly the public sector, is important in the debate over how and how much to publicly fund research in agriculture, and are currently framed against the backdrop of a long running decline in real terms of public funding for research and a gradual strengthening of environmental standards for agriculture in the United States. Should public funding of agricultural research be intensified in order to compete with spending on agricultural research and the fruits of innovation in the private sector as they rival, surpass and, according to some perspectives, come to dominate the efforts of the public sector? Others respond in the opposite by questioning the relevance of spending public dollars to maintain a large public research infrastructure in the face of a vigorous and seemingly more efficient private sector. In general terms, to what extent are the output of the different sectors substitutes and to what extent are they complements?

Since patents are issued to all organizations (public and private) they thus measure contributions of a comparable scientific caliber made by organizations across all three R&D sectors. This paper analyzes a unique data set of 3092 U.S. patents issued between 1975 and 1998, organized into categories or clusters of closely related or 'homologous' technologies that describe the growth or evolution over time of new 'families of biological innovations for agriculture' that follow identifiable sequences or 'trajectories'. The disaggregation of the patent data into separate technological trajectories helps to control for a number of technology-specific effects and allows a comparative analysis of the R&D sectors, and even allows the possibility of extending the analysis to individual research organization, a task that would be difficult or impossible in more aggregate patent data sets. As a branch in a family tree of agricultural knowledge, each patent makes a contribution to the stock of knowledge, as proxied by variables that measure aspects of the ‘quality’ or ‘value’ of the underlying invention. The stock of knowledge in a given technology, gives rise both to new measurable knowledge represented by new patents added each year and to new follow-on product developments. The basic question to be answered is who tends to contributes what kinds of knowledge and when.

2. BACKGROUND AND HYPOTHESES

2.1. Public and Private R&D: Cross-sectoral analyses of innovation

Kenneth Arrow (1962) observed that the results of innovation (i.e. knowledge) are innately characterized by indivisibility, inappropriability, and uncertainty and concluded therefore that perfect competition fails to optimally allocate resources for innovation, and the resulting underinvestment is mitigated by non-optimal interventions. Two broad areas of economic investigation concentrate on the two broad types of such interventions: private and public. The former has focused more closely on institutions and incentives for the private supply of innovation and the industrial organization of R&D (Mansfield, 1968; Nordhaus, 1969; Rosenberg, 1971; Nelson and Winter, 1982; Griliches, 1984; Scherer, 1984; Cohen and Levin, 1989). The latter has concentrated on the public supply of innovation, a tradition particularly strong among agricultural economists (Huffman and Evenson, 1993; Alston, Norton, and Pardey, 1998). Empirical studies in these two literatures have also, by in large, focused on one sector or the other. Cross reference in empirical work between sectors is rare, with studies of one sector tending to give only partial, passing, or ‘exogenous’ treatment to the other sector. This state of affairs in empirical work seems to be due largely to the widely divergent types and availability of data across the public-private divide.

Four specific lines of work, however, have attempted to make (or have at least left room for) direct systematic comparison of public and private R&D across the sectoral divide. Many of them seek to address or to test a fundamental conventional hypothesis that policy makers, business managers, and economists have long used: the reductionistic sequential or ‘linear’ model of the innovation-commercialization process, in which a new idea is characterized to flow from its inception as basic science in a publicly sponsored research lab through the proverbial R&D pipeline until it is applied as a technology in commercial products and is taken to market.

Research theoretic and induced innovation models (Hayami and Ruttan, 1985; Evenson and Kislev, 1973; Binswanger, 1974): Distinctions are not drawn in these models as to whether the research decision maker is a private or a social optimizer. The decision to invest is determined by the expected returns to a random innovation process, which depend upon economic conditions particularly upon the relative endowments and thus the relative prices of inputs in the economy. The technological innovation outputs are economically differentiated as labor-saving or capital-saving.

Political economy of public goods investment (de Gorter and Zilberman, 1990; Gardner, 1988): These models analyze political economic considerations for investment in public goods, determining levels of investment and shares of the investment burden between public and private sources. A common simplification in these studies is to treat the public good output of the innovation process as essentially homogeneous.

Public research spending as complement or substitute to private research spending (Reviewed in David and Hall, 1999 and David, Hall, and Toole, 1999): Complementarity and substitution between public and private R&D efforts are measured in amounts of R&D dollars invested: when public investment in R&D changes, how are returns to private R&D calculated to change?

Patent bibliometric analyses: Who cites whom? Who collaborates with whom? (Cockburn and Henderson, 1996; Jaffe and Trajtenberg, 1996; Perko and Narin, 1997; Jaffe, Fogarty, and Banks, 1998): Such studies analyze the patterns of patent citations to other patents and to scientific publications in order to track flows of knowledge across institutional boundaries. Others analyze co-invention of patents and co-authorship of scientific papers as evidence of research collaboration and knowledge sharing. Cockburn and Henderson empirically examine the immediate flow of knowledge between public and private researchers in the pharmaceutical industry in their analysis of coauthorship of research papers. They find a significant amount of coauthorship between public and private resarchers, leading them to appraise the "simple linear model of the relationship between public and private research" as "misleading".

A number of other studies that have examined the relationship between public and private sector R&D and have challenged the applicability of a model of directed or 'linear' progression in research and innovation between the sectors. Rosenberg (1994) points to the bi-directional flow of knowledge between high-powered corporate research labs and universities, on what he calls the "two-way street". Etzkowitz (1998) envisages technology transfer as "a two-way flow from university to industry and visa versa," or more elaborately as "a non-linear recursive interaction between theory and practice, academia and industry." Gibbons et al (1994) point out specifically that, "Recent examples of research in which theoretical advances have occurred in tandem with the invention of devices or innovation in methodology in transistors/semiconductors, superconductivity, and genetic engineering have called into question the one-way flow of knowledge from basic to applied research in industrial innovation." Specifically in agriculture, Huffman (1998) dismisses a direct one-way relationship between science and technology, citing the long history in agriculture of practical on-the-farm problem solving driving the agenda for basic research.

Several disparate challenges encumber the cross-sectoral analysis of R&D and makes generalizations about the relative roles of the sectors difficult to formulate. Data itself tends to be sector-specific, both in how it is collected and in what it reflects even if it appears on the surface to correspond. Also, multiple levels of analysis and frames of reference present themselves for analysis of the relative roles of R&D. Not all are meaningful or appropriate to such questions such as how and whether public sector research informs private sector development. In an attempt to overcome some of these challenges and provide comprehensive cross-sectoral analysis, the following approaches are explored in detail: the use of comprehensive patent data that spans all R&D sectors, the construction of samples containing highly homologous technologies as an optimal level of controlled comparison, and the use of patent citations and other indicators of economic heterogeneity to characterize qualitative differences.

2.2. Patents as systematic indicators of R&D output

The use of patent data for economic analysis has been well established and the place of patents in the complex economic knowledge generation process has been clarified (Griliches, 1990). Patents are considered a proxy measure of knowledge capital: according to Griliches the generation of economically valuable knowledge can be specified as a general knowledge production function in which patents are created as a byproduct. While knowledge goes on to produce ultimately valuable outputs, a patent remains as a static claim over an invention that was made at one point in time.

Patents by no means represent all of the economically useful knowledge generated in the economy, nor even in just the private sector. An econometric valuation study of French, British, and German patents by Schankerman and Pakes (1986) implies that the aggregate value of patents is only 10 to 15 percent of the total national expenditures on R&D. Duguet and Kabla (2000) find that on average French firms register patents for only one third of their innovations. It is clear that there is not a one to one relationship between underlying technological innovations (which are not always observed) and the legal documents issued to protect the intellectual property rights of the inventing party (observed).

A patent is a standardized legal document that is granted to any R&D organization or inventors from any R&D sector of the economy following consistent standards when a basic set of criteria is met. As a result the U.S. Patent and Trademark Office (USPTO) has provided in the public patent record a source of data useful for systematically comparing the inventive outputs of the different R&D sectors.

2.3. Heterogeneity of research paradigms and natural trajectories of inventions

Research and development does not advance uniformly but rather proceeds according to characteristically variegated patterns. New technological advances tend to cluster within specific ‘research paradigms’, general accepted or feasible ways to approach solutions to specific sets of problems (Nelson and Winter, 1977). Radical innovations may define a new approach to solve an existing problem, but may also create imbalances that cause new problems, calling for incremental inventions to fix and fine tune the technological solutions offered under a given paradigm (Rosenberg, 1974). As inventions inspire inventions over time, the technologies defined within the boundaries of specific paradigms are observed to grow along ‘natural trajectories’. Such ***technological***

trajectories are sequences of innovations where "advances seem to follow advances in a way that appears somewhat 'inevitable' and certainly not fine tuned to changing demand and cost conditions," as opposed to following the logic of optimization on the margin as predicted by induced innovation models (Nelson and Winter, 1977). A natural trajectory, therefore, is defined by the opportunities for advancement, which are in turn defined by technological parameters.

However, a set of highly similar or related innovations that constitute a single trajectory while assumed to face similar conditions of technological opportunity (technology push), also face similar levels of demand for application in final goods markets (demand pull) and contemporaneous administrative policies, regulatory requirements, and treatment under intellectual property law (transaction costs). Since research in all sectors in the same technology faces the same ultimate environmental factors equally, identifying patents to belong to a specific technological trajectory serves to control for the effects of these environmental factors on propensities to patent. Yet, within a designated set of technologically related patents, there is still significant variation in other, more standard qualitative characteristics. Thus, for the purpose of comparing R&D outcomes of different sectors, the technological trajectory offers, in principle, a naturally way to construct a patent sample.

2.4. Qualitative economic heterogeneity among inventions

Statistical methods based on the previously untapped richness of patent data have recently been developing standardized measures of qualitative technological and economic aspects of innovations (Henderson, Jaffe, and Trajtenberg, 1995). By definition, all technologies share the common economic characteristic that they produce an outward shift in a production possibilities frontier. Beyond that, technologies have two other basic common economic characteristics: their use is, in principle, non-rival, and their invention is, by in large, uncertain. But the assumed similarities end there. The most interesting heterogeneous characteristics of innovations that have been elucidated in recent studies with patent data are basicness, quality (or importance), value, and uncertainty. Not all of these characteristics are separable in practice.

Basicness: By definition, basic innovation precedes and enables applied innovation (NSF, 1995). As pointed out by Trajtenberg, Henderson, and Jaffe (1997) this distinction, as commonly used in policy discussions is made in reference to the research inputs of an innovative process, but that it similarly applies to the outputs of an innovation process, which are measured by patents.

The 'basicness' of innovation outputs has both a scientific-technical interpretation and an economic interpretation. In the scientific-technical interpretation, as tools that enable further innovation, basic innovations will tend to occur earlier in a trajectory all other things being equal; yet, it is not uncommon for engineers to create applied technologies without fully understanding the science that explains why they work. Similarly, sometimes it is only possible to go further in the basic research of a particular technology field after certain applied innovations have been made. In the economic interpretation, basic innovations, when considered as knowledge capital, exhibit low degrees of asset specificity and can be deployed in a wide range of production activities. Applied innovations, on the other hand, when viewed as assets, are constrained by high degrees of specificity to a narrow range of production activities. Bresnahan and Trajtenberg (1995) describe basic '*enabling technologies*' as opening up new opportunities for application in multiple economic sectors.

Trajtenberg, Henderson, and Jaffe (1997) propose several measures of the basicness of a patented innovation based on data from the patent records: the number of subsequent patents that cite the subject patent; the number of previous patents cited by the subject patent; and the number of other scientific and technical paper references cited by the subject patent. The most significant predictor of basicness in their model is the count of forward patent citations.

In this use, as a measure of basicness, forward patent citations represent a link, a causal or teaching relationship between the respective documents, a knowledge flow. If a patent has been shown to cause or to teach more patents after it, the innovation that it represents is considered more basic. Similarly an innovation is considered more basic if its patent draws on or synthesizes from a greater breadth of cited sources, both previously published patents and scientific papers. Patents with fewer citations in either direction are considered more narrowly focused on a particular problem, and thus more 'applied'. Whereas this use of citations to measure basicness is in some sense 'self-referential' (because the definitions of 'basicness' and the significance of a 'citation' are interdependent), two recent studies show that the citations measure of patent quality is statistically correlated to real measures of the welfare impact of the cited patent.

Quality or Social Value: While the quality or social value of the underlying economically significant knowledge is not observable, the *quality* of a representative patent can be significantly estimated *ex post* by a number of indicators, the most important of which is forward patent citations (Trajtenberg, 1990). In speaking of the quality or importance of an invention there is also emphasis on its purely scientific and technical impact.

Lanjouw and Schankerman (1999) use a latent variable model to estimate a composite index of the *quality* of a patent based on the following quality indicator variables including: the number of claims made by the patent, the number of citations that a patent makes to other patents, the number of citations a patent receives after five years, being part of a large 'patent family'. They find that the composite index of quality is significantly correlated with two kinds of costly economic decisions: whether to defend the rights to the patent in court (litigation opposition) and whether to pay the requisite fee to renew the patent with the USPTO.

Private Value: Another closely related characteristic, by which the 'size' of a new 'piece of knowledge capital' can be measured, is a patented invention's *value*, that is, the magnitude of the impact that the new knowledge will have on the private welfare of the producer or other immediate user of that intellectual capital. At the current level of precision, empirical studies do not effectively differentiate 'private value' from 'social value', as the two are highly correlated in the available indicators. In speaking of 'private value' there is greater emphasis on demonstrable or measurable economic impact of an invention.

Hall, Jaffe, and Trajtenberg (1999) find that the number of eventual citations to a patent held by publicly listed firms is positively correlated with a market valuation of that patent as calculated from the 'announcement effect' of that patent's issue on the firm's stock market value. They find that, as a measure of the expected value of a patent, forward citations are as significant as R&D expenditures, which has long been established as the best available prediction of a patent's value (Griliches, Pakes, and Hall, 1987). In the analysis. Because of significant variation in patent citation frequencies across time and technologies and a severe truncation problem, the citations measure is quite noisy. Hall *et al* work out several corrections for these by fitting a model for the probability of citations to an extremely large historical set of patent, thereby deriving weighs to correct for changes in frequency and truncation.

Harhoff, Scherer, and Vopel (1999) find the following indicators to be significantly correlated with the value of patent rights as revealed by German patent holders in a detailed valuation survey: the number of citations a patent receives; the number of citations that a patent makes to other patents; the number of citations that a patent makes to the non-patent scientific literature; a patent being upheld against litigation opposition; and a patent being part of a large "patent family" (i.e. one of corresponding patents taken out in different countries on the same invention).

In this use as a measure of value, forward patent citations are treated almost as responses in a survey of experts in the particular field of knowledge who have been selected by the fact that they have themselves applied for and received a patent (or they are the patent examiner reviewing the application for a patent). The legal role of patent citations is both to identify the similarities and to establish the differences between inventive works. A citation is essentially a response to the question, "What are the most valuable inventions made in this field of technology, such that either you have built upon their contributions, or you need to establish that the scope of those inventions do not encroach upon the claims you have made to have invented something novel and non-obvious?"

Uncertainty: The research-theoretic (Evensen and Kislev) and induced innovation (Binswanger) models specify that when contemplating new research projects, researchers have expectations about the mean and variance of the probabilities of success given the particular technological fields in which they are working and the stock of knowledge in those fields that has already accumulated and on which they are attempting to build. By choosing different lines of research, the individual researcher is choosing different lotteries. The researcher's problem is the same as an investor's problem, but instead deciding on a research portfolio rather than an investment portfolio.

Taken together, the use of patent data in order to observe systematically the output of all R&D sectors, sampling from 'technological trajectories' to control for exogenous systemic effects linked to specific types of technologies represented by patents, and measuring the qualitative heterogeneity of technologies represented by patents within technological trajectories, provides a new empirical framework within which to revisit questions of the relative roles of different kinds of research organizations.

2.5. The questions of this study

A starting point for forming hypotheses about the roles of public and private researchers in generating biotechnologies for agriculture is found in a systematic compilation of case studies of the biotechnology industry by Zilberman, Yarkin, and Heiman (1998). Drawing from numerous interviews with practitioners in biotechnology, they report five common sequential patterns through which new technologies are developed, scaled up, and commercialized. These patterns vary according to which kind of organization undertakes which stage of a technology's commercialization.

Table 1. ***Alternative Mechanisms for Product Innovation***

Pattern	Research	Development	Registration	Production	Marketing
1	U	I	M	M	M
2	U	M	M	M	M
3	U	I	I	M	M
4	M	M	M	M	M
5	I	I	M	M	M

U = University, I = Startup, M = Major corporation
Source: Zilberman, Yarkin, and Heiman (1998)

This collection of patterns shows that, while in some phases of the innovation process, notably in the 'research' phase, involvement may be observed of any of the three types of organizations, and 'lateral R&D spillovers' between technologies may be observed to flow in any direction among organizational types. The key observation here, however, is that the progressions *along* the stages of innovation and commercialization always consist of 'university' before 'startup' or 'corporation' and always 'startup' before 'corporation', and never 'corporation' before either 'university' or 'startup'. In order to trace these patterns, however, it is important to be talking about a single particular technology. If two different technologies are of different patterns or are at different points of progression of the same pattern at the same point in time, comparing across those technologies would mean blurring together distinctions of their individual patterns.

By more clearly defining the assumed relationships among the abstract concepts and the observable characteristics of research outputs, a framework can be constructed in which hypotheses of the relative roles of the different R&D sectors can be meaningfully formulated and cast in the form of questions that can be answered with the available data.

Assumption 1: Basic ⇔ Earlier in trajectory

If certain innovations in an identified technological trajectory are more basic than others, in the sense that the basic innovations are antecedent to other innovations in that trajectory, we would expect the patents protecting those basic innovations to show up earlier in the trajectory, all other things being equal.

Assumption 2: Basic ⇔ (high Uncertainty = high variation in Value or Quality)

Because of the uncertainties involved in basic research[1], the basic innovations[2] that result from it tend to vary more widely in terms of their value or quality than applied innovations. The mean expected value of basic innovations may be equal to the mean expected value of more applied innovations, but the variance is greater: there is a greater probability of very high value and of very low value among basic innovations than among applied.

Assumption 3: Value or Quality ⇔ Citations

The value or quality or importance of an innovation is revealed by citations made to the patent protecting that innovation. Those patents that garner the most citations in a technological trajectory represent the trajectory's most important or valuable innovations.

Implication 1: Basic ⇔ (high variation in Citations)

Implied by the combination of assumption 2 and assumption 3.

Implication 2: (Highly cited = High Value or Quality) ⇒ Basic

Implied by the combination of the upside of the uncertainty in assumption 2 and implication 1. Looked at another way, a basic research project that does not succeed gets little or no citations, with more probability than applied innovations. Basic "failures" are not often cited. On the other hand a basic research project that does yield a success, will get many citations, also with more probability than applied innovations. Therefore, if a patent is observed that has many citations, it is more likely to be a basic innovation.

Note that because of the nature in assumption 2 of uncertainty having both an upside and a downside, implication 2 does not run backward: A basic innovation is not necessarily highly cited. There is not a one-to-one between basic innovations and citations.

Implication 3: Higly cited ⇔ Earlier in trajectory

[1] Here 'basic' defines parameters of the knowledge production function…

[2] …while here 'basic' characterizes the output from that function. However, it should not be interpreted as a general rule that only 'basic' research generates 'basic' research outputs, or visa versa, see Henderson, Jaffe, and Trajtenberg, 1995, for an insightful discussion on the relationship between characteristics of research inputs and outputs. This paper concentrates on characteristics of the outputs.

Implied by the combination of implication 2 and assumption 1.

Finally we have yielded a question that data allow to be asked:

Question 1: *In an identified technological trajectory, do the most highly cited patents (after citation counts are corrected for truncation) show up earlier in the trajectory?*

The answer to this question tests the integrity of these arguments, the construction of the technological trajectories and the patent citations measures against the predictions of the theoretical arguments.

Now, with the exception of implication 2, the above assumptions and corollaries can be inverted for applied innovations.

Assumption 4: <u>Applied ⇔ Later in trajectory</u>

If some innovations in an identified technological trajectory are more applied than others, in the sense that the applied innovations are descendents of other innovations in that trajectory, we would expect the patents protecting those applied innovations to show up later in the trajectory, all other things being equal.

Assumption 5: <u>Applied ⇔ (Low Uncertainty = low variation in Value or Quality)</u>

Applied innovations cover a narrow spread of values or qualities. Because of the greater certainties involved in applied research, the applied innovations that result from it tend to vary much less in terms of their value or quality than basic innovations. The expected value of applied innovations may be equal to the expected value of more basic innovations, but the variance is less: there is less probability of very high quality and of very low quality among applied innovations when compared to basic innovations.

Implication 4: <u>Applied ⇔ (low variation in Citations)</u>

Implied by the combination of assumption 5 and assumption 3.

Now based on these assumptions and implications, hypotheses about the specialization of different types of research organizations can be stated and tested.

Hypothesis 1: <u>University and Public ⇔ Basic Innovation</u>

If universities and public research institutes truly have a comparative advantage in technological genesis and specialize in basic innovation, we would expect to observe patents that belong to universities and public institutes according to the predictions of the above assumptions and implications about basic innovations.

Question 2: *In an identified technological trajectory, do universities and public research institutions tend to patent more in the early phases of a technological trajectory than in later phases of the trajectory?*

Question 3: *In an identified technological trajectory, do universities and public research organizations tend to have a higher proportion of the most highly cited patents compared to other organization types?*

Question 4: *In an identified technological trajectory, do universities and public research organization patents tend to have a higher variance of citations than others?*

Hypothesis 2: <u>Corporation ⇔ Applied Innovation</u>

If corporations have a comparative advantage in technology utilization and specialize in applied innovation, we would expect to observe patents that belong to corporations according to the predictions of the above assumptions and implications about applied innovations.

Question 5: *In an identified technological trajectory, do corporations tend to patent more in the late phases of a technological trajectory than in earlier phases of the trajectory?*

Question 6: *In an identified technological trajectory, do corporations tend to have a lower proportion of the most highly cited patents than others?*

Question 7: *In an identified technological trajectory, do corporate patents tend to have a lower variance of citations than others?*

Hypothesis 3: <u>Startups ⇔ Between Basic and Applied Innovation</u>

If entrepreneurs and startups companies have a comparative advantage and thus specialize in the development, commercialization, and marketing of basic innovations (i.e. in turning basic innovations into applied innovations), we would expect to observe patents that belong to entrepreneurs and startups to split between the predictions made for basic and applied innovations.

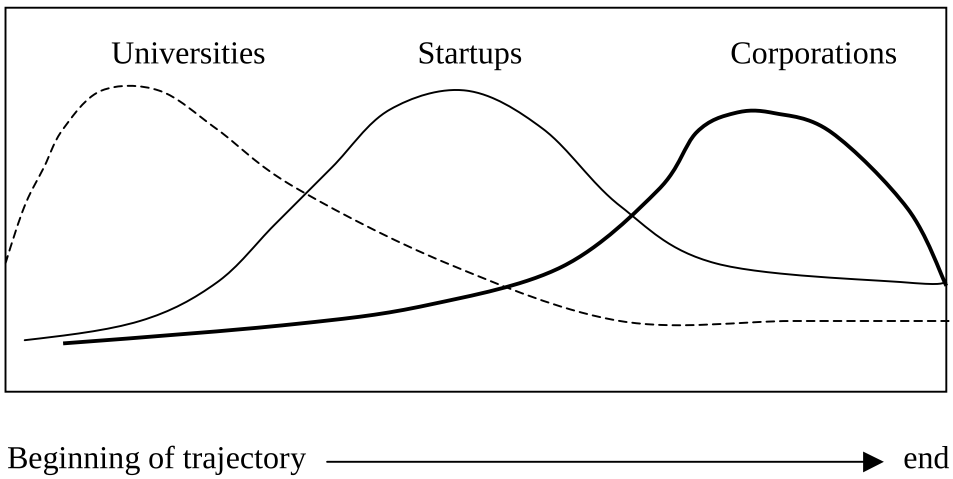
Question 7*: In an identified technological trajectory, do startups tend to patent more in the middle phases of a technological trajectory?*

Question 8: *In an identified technological trajectory, do entrepreneurs and startups tend to have a higher proportion than corporations but a lower proportion than universities of the most highly cited patents?*

Question 9: *In an identified technological trajectory, do the patents of entrepreneurs and startups tend to have a higher variance of citations than corporations but lower than universities?*

Figure 2 illustrates the general hypothesis that universities have a higher probability of contributing to the stock of knowledge near the beginning of a trajectory, corporations are more likely to contribute to the stock of knowledge toward the end of a trajectory and startup companies more likely to be found filling the gap between the two.

Figure 1. ***Hypothesized trends in the probabilities of the three types of research organization contributing to the stock of knowledge over the course of a technological trajectory***



3. THE DATA

3.1. U.S. patents on agricultural biotechnologies, 1975-1998

In order to answer these questions, a comprehensive database was constructed of *all* U.S. patents for biological inventions pertaining to crop agriculture granted to all types of assignees (public and private) over the 23 years from 1975 through 1998. A complex sampling problem was faced in trying to identify which patents out of the millions issued between 1975 and 1998 represented the knowledge stock of biology for agriculture.

The U.S. patent data contain two different coding systems for the technologies described in a patent: one is the U.S. Patent Classification (USPC) system; the other is the International Patent Classification (IPC) system. Both of these systems intend to provide an indexation to aid inventors and examiners in searching the patent data for ‘prior art’ when a new patent is applied for, in order to verify that a previous patent has not already been issued that already makes claims over aspects of the new invention. The USPC system has evolved slowly over the more than 200 years that the U.S. Patent and Trademark Office has been issuing utility patents and thus lacks the benefit of hindsight categorization, particularly in high technology areas such as biotechnology. The IPC system was more recently devised and thus makes a more careful parsing of technologies. Several IPC categories are specific to plant biology and agriculture. However, most agricultural biology patents are located under other classifications not specific to plant biology or agriculture, and a large fraction of the patents within the classes that contain a preponderance of the agbio patents are not agbio patents.

A four-pronged search strategy was employed and iterated exhaustively. First, keyword searches were carried out utilizing a long list of technology terms derived from the CAB Abstracts and several industry reviews as well as English and Latin names of all major crop and experimental plant species. The patents retrieved as results of each search were then read over and reviewed: those that were clearly agricultural biology patents were retained in the growing sample, while all others were discarded. Second, IPC subclasses found to be commonly occurring in the sample resulting from the first step were searched. Again, the resulting new patents were read and reviewed, with agbio patents retained and added to the sample and all others discarded. Third, all patents that were *cited by* the patents in the growing sample were read and reviewed, and respectively added to the sample or discarded. Finally, all patents that *cited* the patents in the sample were read and reviewed. The search process was considered complete and exhaustive once the iterated searches consistently turned up only patents that were already in the sample. By that point the sample consisted of 3092 U.S. patents.

3.2. Constructing technological trajectories from patents in the sample

Once all agricultural plant biology patents were isolated, the next immediate question was how to organize them into separate research paradigms, in order to be able to trace the growth of the natural technological trajectories of agricultural biology with the patent data. However, experience shows that neither the USPC nor the IPC system is able to categorize patents with sufficient precision to cluster patents into economically meaningful ‘technological trajectories’[3].

Instead, when each of the 3092 patents was read it was determined to belong to one or more of a set of agricultural biology classifications created for this purpose. (An exhaustive list is provided in Appendix A.) These classifications serve as unique identifiers of all the different types of research paradigms and associated technologies encountered in the comprehensive search for agricultural biotechnology patents. They are highly specific and designed to capture the dual criteria of (1) ‘novelty’ and (2) ‘utility’ of the invented technology[4]: how it represents a technically new contribution and how it is expected to be economically useful in solving real problems in agriculture.

[3] For example, patents over “plant genetic transformation methods” are scattered over a dozen different major IPCs.

[4] The third basic requirement of “nonobviousness” is no longer germane after a patent has been published.

These combined novelty-utility disclosures dictate each of the technical-economic agricultural biology classifications and allow each of them in theory to encompass an emerging technological trajectory. The relatively high degree of ‘technological homology’ among patents in each of the agricultural biology classifications is verified both by the tight similarity of key technology concepts and interrelationships via citations inter-linkage among the patents. The iterative keyword and the cited and citing searching technique established the integrity of this ‘trajectory’ nature of the individual agricultural biology class. Indeed, in some cases several ‘generations’ of citing and cited patents were gathered together in a single agricultural biology class.

It is not practical for purposes of statistical analysis however to use the individual agricultural biology classes as separate samples; they contain on average such small numbers of observations as to challenge any asymptotic assumptions that would be necessary for most estimation techniques. Instead these agricultural biology classifications were aggregated, with 2428 of the patents clustering into thirty major technology groups that represent more general technological trajectories. The level of aggregation chosen for these thirty patent samples is a result of the trade-off between defining a technological trajectory narrowly enough to effectively control for systematic effects versus defining a trajectory widely enough to have a sufficient number of observations to allow for statistically meaningful analysis.

Table 2 shows for each technology the total number and the percentage of patents that have accrued to each type of institution in the years 1975-1998. A total of thirty ‘technological trajectories’ have been constructed with an average of 100 patents per trajectory. The smallest trajectory has 37 patents and the largest has 298 patents. Patents are each allowed to span up to four trajectories. For instance, a patent for a hybrid corn parent variety modified with a male sterility gene will be identified as a contribution to both the “corn germplasm” trajectory and the trajectory of “genetic traits for control of reproduction”.

3.3. Variables

Data collected for each patent includes all of the patent’s “front page” matter, which includes information such as the patent number, title, inventor, assignee, application and issue dates, IPC and USPC codes, and more. Textual content of the patent, such as the abstract, the list of legal claims made by the patent, and the body of the patent were used to decide upon the agricultural biology classification of the patent, for which a code variable was assigned. Additional data include the lists of reference citations, both the prior patents and the scientific literature that the applicant and the reviewing patent examiner deemed relevant to the patent. From these raw data a number of variables can be extracted or constructed to serve as indicators of the techno-economic characteristics (Section 2.4) of the patent and the state of the relevant technological trajectories (Section 2.3) to which the patents belong.

Weighted forward patent citations: Direct measures of the degree of 'basicness', social value, and private value of patents have all been significantly correlated in the literature with the counts of the forward citations made to the patents, establishing this variable as a significant indicator of the fundamental technological and economic impact of the invention represented by a patent, which can be most generally thought of as the patent's contribution to the (unobservable) stock of economically significant knowledge or the value of its 'knowledge capital'.

For a patent *n*, applied for in year *t*, the weighted sum of forward patent citations, c_{nt}, made to by patents applied for after year *t* but before the present (or terminal) year *T* when the number of citations is observed, is designated

$$\text{WCITES}_n = \omega_{A(t)} \sum c_{ntj} \text{ .}$$

Because the forward citations of more recent patents are truncated by not being able to know now (in terminal year *T*) citations that will be made in the future (after *T*), the forward citations count is weighted by ω_A, which is a correction derived from a fitted citations lag distribution (Hall et al, 1999) and is specific to the age of the patent at the time *T* when citations are counted: $A = T - t$.

The existing stock of economically valuable knowledge in a technological trajectory: Over time, the stock of knowledge capital grows by the addition of new knowledge from each patent. The total existing stock of knowledge in trajectory *j* at the time that a patent *n* is applied for can be represented by the sum of weighted forward citations of all the patents in the sequence of trajectory *j* prior to the arrival of patent *n*:

$$\text{ESTOCK}_n = \sum_{i=1}^{n-1} \left(\omega_{Ai} \sum \left(c_{itj} \right) \right)$$

Note that the contribution of patent *n* itself is not included in this sum. This variable attempts to measure the point of progress in the technological trajectory at which an invention is made. It also represents, within the limitations posed by the use of patents alone, the amount of general knowledge or prior precedents within that particular paradigm from which an inventor might have drawn in making her contribution.

In this framework it is not necessary to include explicit terms for the obsolescence of old knowledge because the weights used, ω_A, calculated from sample distributions of actual citation lags, account for the drop-off in the trend of citation that accompanies the aging of a technology.

Other qualitative indicator variables, suggested by the studies reviewed in Section 2.4, which can be derived either directly from the raw patent data or from other secondary sources, include the following:

- The number of previous patents cited (backward citations), as a measure of basicness
- The number of scientific and technical paper references (non-patent citations), as a measure of basicness
- The number of claims made by a patent, to measure quality/importance/value;
- A dummy variable for having faced litigation, as a measure of quality/importance/value
- A dummy variable for having faced an administrative review or opposition at the patent office, as a measure of quality/importance/value
- A dummy variable for being a member of an international patent family (or at least for having a PCT filed) as a measure of quality/importance/value
- Ratio of forward patent citation made by the patent's assignee (self forward citations), as a measure of the appropriability of the knowledge capital represented by a patent
- Ratio of forward patent citations made from patents outside its designated technological trajectory, as a measure of basicness

3.4. Descriptions of the data

Table 2 summarizes the distribution of weighted forward citations for the total of 2428 patents in the thirty technological trajectories separated out by sector. The data in this table already begin to answer the questions posed by the hypotheses of differential roles in Section 2.5. This will be further developed in the results in Section 5.

In order to provide some perspective on what specific organizations are most involved in the biology of agriculture, the top thirty organizations with the most patents in the database are listed in Table 3 below. Notice the presence in these top rankings of a mixture of government (USDA), universities, small biotech firms, and large corporations.

Table 3. ***The top 30 patenting organizations in the dataset***

Organization	Number of Patents	Organization	Number of Patents
Pioneer Hi-Bred International	245	DeKalb	33
Mycogen	160	Sandoz	33
USDA	126	Iowa State University	31
Monsanto	101	Hoechst	30
Asgrow Seed	64	University of Wisconsin	28
Calgene	63	Lubrizol	25
Ciba-Geigy	57	W. R. Grace	23
Zeneca	54	Rhone-Poulenc	22
University of California	53	Agracetus	21
Du Pont	51	Michigan State University	20
Novartis	51	Texas A&M University	20
Holden's Foundation Seed	47	Agricultural Genetics Company	19
DNA Plant Technology	43	American Cyanamid	19
Cornell University	42	Ecogen	19
Plant Genetic Systems	38	North Carolina State University	19

The assignee with the most patents in this data set is Pioneer Hi-Bred, the leading seed company in the U.S. The large majority of their patents cover varieties and hybrids of corn, although Pioneer also commands an impressive portfolio of biotechnologies. The USDA is the largest and most prolific public research institution, with several universities hosting strong agricultural and biology departments also taking prominent positions. Several of the leading agbiotech companies, including Mycogen and Plant Genetic Systems make the list. The corporations on the list, beginning with Monsanto, constitute the corporate sector core of the industry.

Figure 2 showcases plant genetic transformation patents—technology group 9 from Table 2, "Plant genetic transformation vectors and systems: Agrobacterium, electroporation, biolistics, viral vectors, etc."—to illustrate the structure of the trajectory of growth of a particular kind of knowledge. In the first panel the arrival of new inventions is displayed by year. A patent applied for in a given year contributes a height to the bar equal to the weighted number of forward citations that the patent eventually receives in the color of the R&D sector to which the patent is assigned. In the second panel the proportion of each year's new knowledge contributed by each sector is displayed and rather clearly confirms the general hypothesis that university and public researchers contribute relatively more of the early knowledge (a preponderance of blue in the lower left), corporations contribute relatively more of the knowledge late in the trajectory (a preponderance of maroon in the upper right), and startups fill in between the two (heavy emphasis of yellow in the middle.) The third panel displays a cumulative running total of the contributions of each sector to the stock of plant transformation knowledge.

4. AN ECONOMETRIC MODEL

4.1. The data generating process

Research and development in the biological sciences applied to agriculture is assumed to proceed within distinct research paradigms such that the resulting technologies are generated along naturally occurring trajectories, $k = 1 \ldots K$, each of which is assumed to be ensconced within the classification a technological sub-field. Not all technological trajectories are at the same point of maturity in their growth or evolution: some constitute new (and thus perhaps poorly defined) areas of research with little accumulated prior knowledge; others are mature areas with large stocks of existing knowledge already in place.

There are J distinct R&D sectors, $j = 1 \ldots J$, in the economy where for simplicity

$$j = \begin{array}{ll} 1 & \text{for universities and public research laboratories} \\ 2 & \text{for individuals, entrepreneurs, startups, and small businesses} \\ 3 & \text{for corporations.} \end{array}$$

The underlying behavioral model consists of several distinct steps for each observation:

1. A joint decision is made, in one of the sectors, *j*, by a researcher and her research administrator or funding source to undertake a project in a specific research sub-field, *k*. It is presumed, although not observed, that the expected (joint) returns from this research project exceed the expected returns from the next best deployment of the researchers time and talents and the expended resources.

2. With a certain probability, a successful research result is produced that meets the standard criteria for patentability of being a novel, non-obvious, and useful.

3. Another joint decision is made by the researcher and the administrative/funding organization as to whether the (novel, non-obvious, and useful) research result be patented (and thus privatized) or simply published in the public domain. It is presumed, although again not observed, that the expected (joint) returns to having a patent, subject to policy and transaction cost constraints, are non-negative. Thus, with a certain probability, or propensity, depending to no small extent on the type of organization, a patentable research result is applied for and granted.

4. The patent, *n*, the R&D sector of the assignee, *j*, the technological trajectory to which it contributes, *k*, and qualitative attributes of the patent, $\mathbf{X}_n$, are observed.

4.2. The statistical model

Econometric analyses of discrete random outcomes, such as the multinomial logit model, have traditionally been based on a latent variable model of choice behavior (McFaddin, 1974; Ruud, 2000) where each outcome is interpreted as the choice of an individual agent whose unobserved or 'latent' utility, construed as a random variable, is assumed to have been maximized by the observed discrete choice, also a random variable, that was actually made relative to the other available options. However, the statistical model employed to analyze the joint sample distribution of polytomous data and the behavioral model used to describe the unobserved latent variable can be viewed as separate models. Claims that the statistical model is appropriate only if there exists a latent variable are often asserted too strongly, and, regardless, the existence of the latent variable, while useful for the internal consistency of the behavioral hypothesis, is often unverifiable in practice (McCullagh and Nelder, 1989). For the current purposes of this study, instead of identifying a single, behaviorally meaningful latent variable, I simplify the complex decisions effected by the many unobservable parameters and latent behavioral variables at play in the data generating process into a single latent 'black box' probability index that relates the qualitative characteristics of a patent with the probability that it is observed to arise from research at a university, a startup, or a corporation.

Thus, for each observed patent, n, in each technological trajectory, k, the probability index that the technology is invented and patent by the jth organizational type is denoted by

$$\mathbf{y}^*_{nj} = \mathbf{X}_{nj}\mathbf{B} + \boldsymbol{\varepsilon}_{nj},$$

where $\mathbf{X}_n$ is a vector of attributes of the n^{th} patent and the $\mathbf{B}$ are unknown coefficients. The ε_{nj} are the unobserved differences in the probability of that patent arising in the j^{th} type of R&D organization, resulting from unobserved features of the behavioral model including the institutional features of the organization, and are assumed to be i.i.d. random variables with a Weibull probability distribution.

When the j^{th} organizational type actually undertakes the research and receives the n^{th} patent, the observed outcome is described with the J dummy variables where

$y_{nj} = 1$ if the n^{th} patent is issued to the j^{th} organizational type, and
$y_{nj} = 0$ otherwise.

From the probability index equation the probability of the n^{th} patent coming from the j^{th} organizational type is

$$\begin{aligned} P_{nj} &= \Pr[y_{nj} = 1 \mid \mathbf{X}_n] \\ &= \Pr[y^*_{ni} \le y^*_{nj}, \forall i \ne j \mid \mathbf{X}_n] \\ &= \Pr[\varepsilon_{ni} - \varepsilon_{nj} \le (\mathbf{X}_{nj} - \mathbf{X}_{ni})`\mathbf{B}, \forall i \ne j \mid \mathbf{X}_n] \end{aligned}$$

Which is equivalent, given the assumptions made about the distribution of the εs, to

$$P_{nj} = P(y_{nj} = 1) = \frac{e^{X_{nj}B}}{\sum_{i=1}^{J} e^{X_{ni}B}}$$

This can be normalized and written as the multinomial logit:

$$P_{nj} = \frac{e^{X_{nj}B}}{1 + \sum_{i=1}^{J-1} e^{X_{ni}B}}, \qquad \forall i \ne j$$

where the values of the J different ‘P’s are conditional probabilities of a patent’s occurrence in the J different institutions given the explanatory variables.

Because they do not enter the probabilities linearly, the organizational coefficients on these patent attributes, the **B**s, cannot be interpreted directly. However, an interpretation is possible from the definition

$$\ln\left(\frac{\Pr_{nj}}{\Pr_{no}}\right) = X_n' B_{jo} \qquad \text{where } o \neq j = 1, 2, 3$$

or more conveniently for calculations:

$$\frac{\Pr_{nj}}{\Pr_{no}} = \exp\left(X_n' B_{jo}\right)$$

which is the probability ratio of selecting research organization type *j* relative to research organization type *o*. The *q* parameters in the vector **B** are the marginal effects of the *q*th regressor in X_n on the odds ratio.

Since the multinomial logit system is solved by maximum likelihood, testing hypotheses about coefficients follows standard hypothesis testing methods based on the covariance matrix from the maximum likelihood estimation.

5. PRELIMINARY RESULTS

The first set of interesting results from this analysis are found in the totals at the end of Table 2: the three sectors have contributed rather comparable total levels of patented knowledge in agricultural biotechnology, with startups contributing the most, garnering 8360 forward citations (after weighting), followed by the public sector and universities contributing patents receiving a total of 7172 forward citations, and corporations contributing the least, with 6710 total citations, despite the fact that corporations received a significantly greater absolute number of patents. The mean value of university patents, measured by an average of 8.8 forward citations per patent, is thereby estimated to be 39 percent greater than the mean value of startup patents, which have an average of 7.8 forward citations per patent, and 57 percent greater than the mean value of corporate patents, with an average of just 5.6 forward citations per patent.

In the aggregate it is also observed that the values of university patents are considerably more variable. The standard deviation of forward citations to university patents is 19.8, 32 percent greater than the standard deviation of biotech startup patent values, which show a standard deviation of forward citations of 15.0, and 75 percent greater than the standard deviation of corporate patent values. In all three sectors the spread of forward citations is quite high relative to the mean, with standard deviations roughly double the means. As portfolios these intellectual assets are quite volatile. Figure 3 displays aggregate histograms of the numbers of forward citations to patents from each of the three sectors. These histograms show the highly skewed shape of the distribution of patent values in all three sectors, which are emphasized by the fact that the maximum valued university patent has 230 forward citations, the maximum valued biotech startup patent has 175 forward citations, and the maximum valued corporate patent has 127 forward citations. This skewness of values is in accordance with a number of other studies that demonstrate the lion's share of value from a relatively few of the most valuable patents (Castillo et al, 1999; Scherer, Harhoff, and Kukies, 2000).

Regression results for the aggregate data set are displayed in Table 4 below.

Table 4. ***Multinomial logit maximum likelihood estimations on the aggregate data***

	1	2	3
University and Public			
WCITES	.0113 (.0044)	-.0013 (.0000)	.0001 (.0051)
ESTOCK		-.0001 (.0046)	-.0000 (.0000)
FAMILY	-.8747 (.1366)	-.9173 (.1385)	-1.3868 (.1482)
CONTINUATION		.1536 (.1091)	-.2286 (.1224)
Constant	-.2433 (.0640)	.8328 (.1685)	
Trajectory dummies (average)			-.0190 (.3572)
Startups			
WCITES	.0123 (.0042)	.0029 (.0042)	.0007 (.0045)
ESTOCK		-.0001 (.0000)	-.0000 (.0000)
FAMILY	-.7354 (.1199)	-.7693 (.1210)	-.9615 (.1334)
CONTINUATION		.2101 (.0996)	-.0285 (.1145)
Constant	.0255 (.0597)	.7622 (.1625)	
Trajectory dummies (average)			-.1059 (.3358)
Log Likelihood	-2604	-2573	-2171
Pseudo R^2	0.0138	0.0256	0.1779

"Corporate" is base category.
Standard errors in parentheses.

The aggregate and somewhat dilute result nonetheless display consistently negative effects of existing stocks of knowledge on the propensities of universities and startups to patent lending support to the general hypothesis that universities tend to patent earlier in a technological trajectory, when the existing stock of knowledge is still quite small. As the stock grows the probability that a university will continue to patent in that trajectory falls relative to the probability of corporate patenting.

Thirty disaggregated multinomial regressions were run separately for the thirty technological trajectories. In 22 out of the 30 regressions the effect of existing knowledge stock on probability of university patenting vis-à-vis corporate patenting was negative; similarly in 23 out of the 30, the effect on startup patenting was negative. Ten trajectories (less than half) showed the hypothesized trend of universities most likely to patent when the existing stock of knowledge is low, startups follow after universities, and corporations most likely to patent when the existing stock of knowledge is high.

6. PRELIMINARY CONCLUSIONS

Preliminary results are promising but further work is still needed to adequately test the hypotheses presented herein. Comments and suggestions are solicited.

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